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ODP Site 1063 (Bermuda Rise) revisited: Oxygen isotopes, excursions and paleointensity in the Brunhes Chron

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[1] An age model for the Brunhes Chron of Ocean Drilling Program (ODP) Site 1063 (Bermuda Rise) is constructed by tandem correlation of oxygen isotope and relative paleointensity data to calibrated reference templates. Four intervals in the Brunhes Chron where paleomagnetic inclinations are negative for both u-channel samples and discrete samples are correlated to the following magnetic excursions with Site 1063 ages in brackets: Laschamp (41 ka), Blake (116 ka), Iceland Basin (190 ka), Pringle Falls (239 ka). These ages are consistent with current age estimates for three of these excursions, but not for "Pringle Falls" which has an apparent age older than a recently published estimate by ~28 kyr. For each of these excursions (termed Category 1 excursions), virtual geomagnetic poles (VGPs) reach high southerly latitudes implying paired polarity reversals of the Earth's main dipole field, that apparently occurred in a brief time span (<2 kyr in each case), several times shorter than the apparent duration of regular polarity transitions. In addition, several intervals of low paleomagnetic inclination (low and negative in one case) are observed both in u-channel and discrete samples at ~318 ka (MIS 9), ~412 ka (MIS 11) and in the 500–600 ka interval (MIS 14–15). These "Category 2" excursions may constitute inadequately recorded (Category 1) excursions, or high amplitude secular variation.

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1. Introduction

[2] Ocean Drilling Program (ODP) Leg 172 to the Blake-Bahama Outer Ridge and Bermuda Rise took place during February–April 1997. ODP Site 1063 [*Shipboard Scientific Party*, 1998] is located on the Bermuda Rise at 33.69°N, 57.62°W and 4584 m water depth (Figure 1). At the time of drilling and to some extent today, geomagnetic excursions,

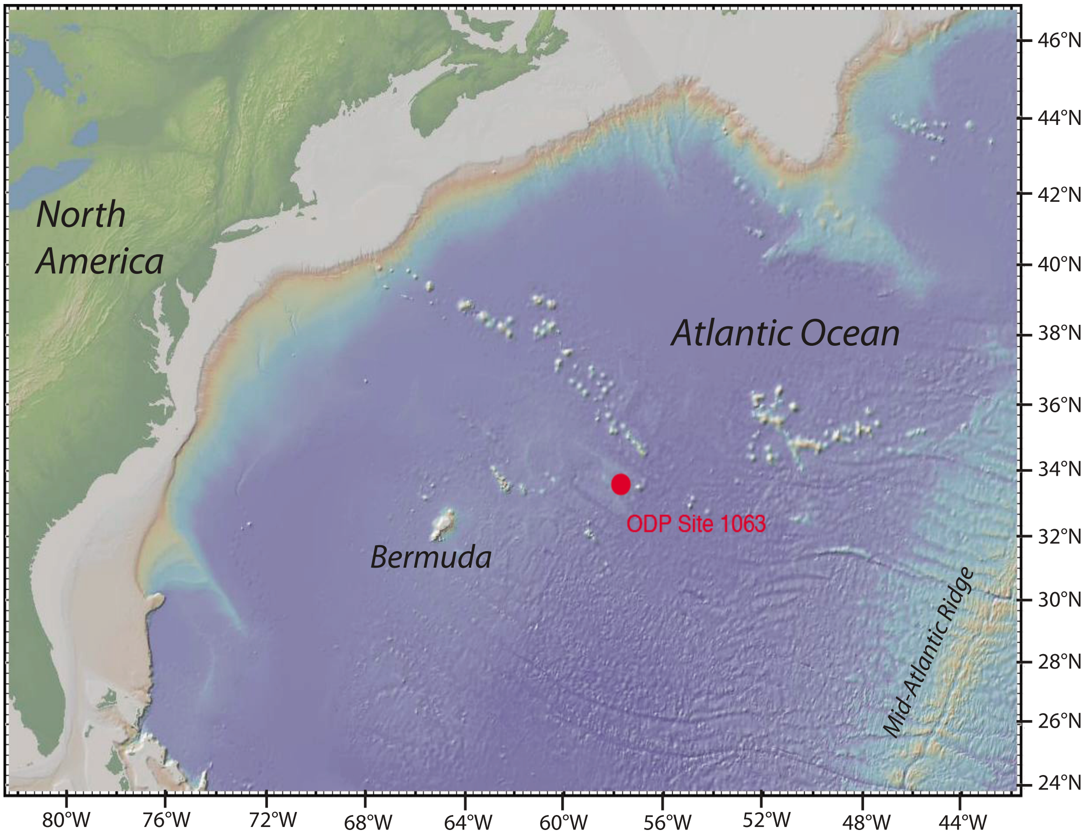

Figure 1. Location of ODP Site 1063 on Bermuda Rise (map processed using GeoMapApp© software).

which we define here as brief directional aberrations of the main dipole field outside the range of expected secular variation, remain controversial. Poorly correlated records of apparent excursions from lavas and sediments can often be assigned to sampling artifacts, sedimentological phenomena, volcanic terrane effects, or local secular variation, rather than behavior of the main dipole field. Although records of magnetic excursions date from the 1960s, the consensus in 1997, at the time of drilling at Site 1063, was that about 5 excursions had occurred in the Brunhes Chron [e.g., *Opdyke and Channell*, 1996], which were named according to locations where they were initially recorded: Mono Lake (~28 ka), Laschamp (~42 ka), Blake (~110 ka), Pringle Falls (~218 ka) and Big Lost (~565 ka). When shipboard studies from ODP Leg 172 indicated 14 Brunhes Chron magnetic excursions characterized by low or negative inclinations [*Lund et al.*, 1998], the results were significant not only to our understanding of the geomagnetic field, but also for (magnetic) stratigraphy. Subsequent shore-based studies [*Lund et al.*, 2001a, 2001b] increased the number of Brunhes Chron excursions to 15, of which 11 were recorded in one or more of four holes at ODP Site 1063. More recent reviews of the status of excursions in the Brunhes Chon have listed 17 excursions in the Brunhes Chron [*Lund et al.*, 2006], 12 excursions in the Brunhes Chron [*Laj and Channell*, 2007] and 13 excursions in the Brunhes Chron [*Roberts*, 2008], respectively, but without clear consensus on excursion ages.

[3] Shipboard studies of ODP Leg 172 sediments entailed demagnetization of archive halves of core sections up to peak fields of 20 mT, occasionally 30 mT and rarely 40 mT [*Shipboard Scientific Party*, 1998]. Shore-based studies on Site 1063 sediments have been carried out on u-channel samples ($2 \times 2 \times 150$ cm^3 plastic containers with a square cross-section and clip-on lid constituting one of its sides) from Hole 1063C in the vicinity of excursions 3α and 3β in marine isotope stage (MIS) 3 [*Lund et al.*, 2001a], and in the interval of excursions 13α-14α (MIS13–14) [*Lund et al.*, 2001b]. In addition, a u-channel study has been carried out in the vicinity of the Cobb Mountain Subchronozone (~1.2 Ma) at Site 1063 [*Yang et al.*, 2001]. *Yang et al.* [2001] calculated component magnetization directions from stepwise demagnetization data, however, other magnetic studies of Leg 172 sediments provide magnetization directions

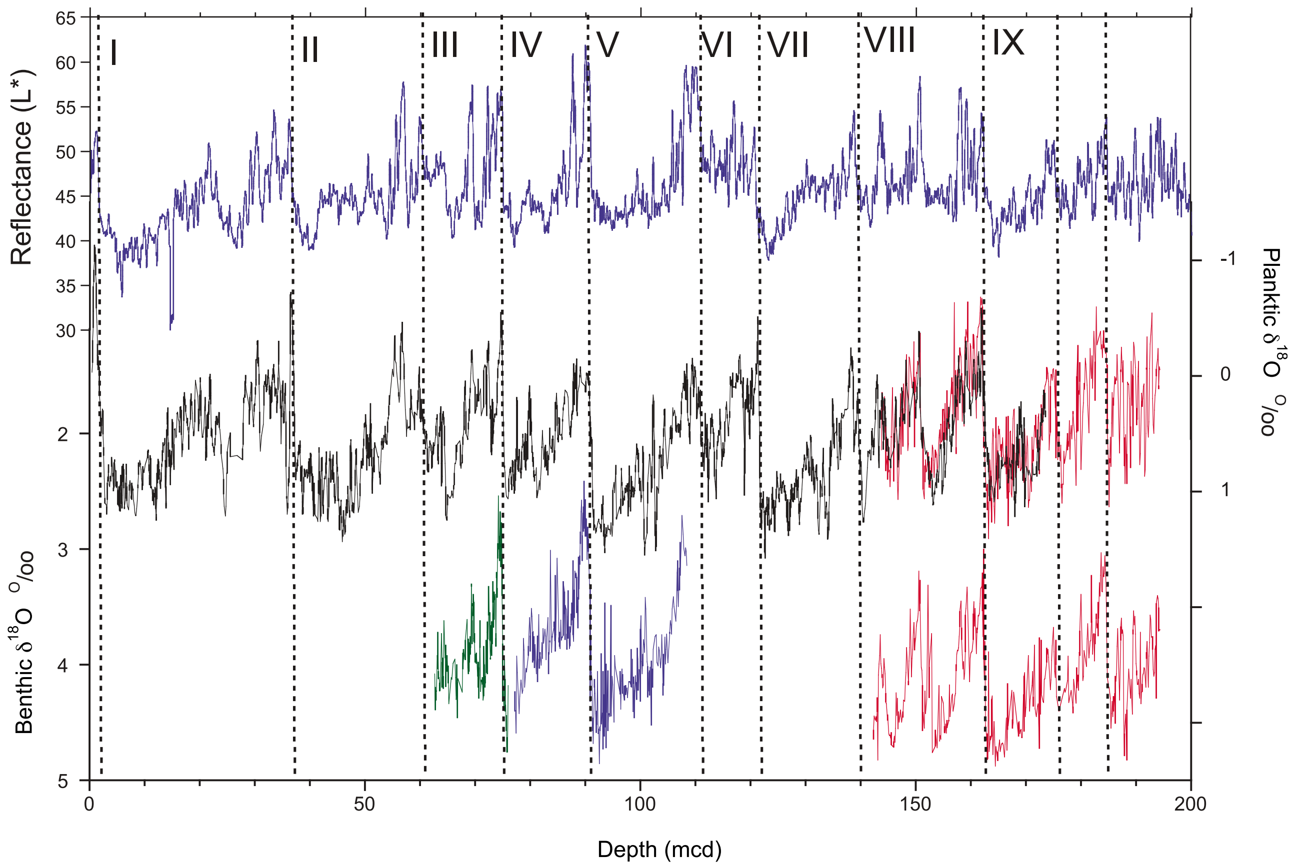

Figure 2. Site 1063 color reflectance (L*) data (blue) [*Shipboard Scientific Party*, 1998] compared with 5-point running mean of δ^{18}O from *Globigerinoides ruber* (black, this paper) and with the planktic and benthic δ^{18}O for the 142–194 mcd ka interval from *Ferretti et al.* [2005] (red), and benthic δ^{18}O records from *Poli et al.* [2000] in the 77–108 mcd interval (blue), and *Billups et al.* [2011] in the 62–75 ka interval (green). Terminations marked by Roman numerals.

only for single demagnetization steps. Component magnetization directions and paleointensity data across the Matuyama-Brunhes boundary at Site 1063 have been reported by *Channell et al.* [2010].

[4] The published age models for the ODP Leg 172 sites were based on tuning filtered records of carbonate percentage, derived from color reflectance (Figure 2) calibrated with shipboard and post-cruise carbonate measurements, to the astronomical solutions for precession and obliquity [*Grützner et al.*, 2002]. The age models are more robust for the shallow-water Leg 172 sites (Sites 1055–1059) than for the deeper water sites (Sites 1060–1063). Precession-related cycles are weak, particularly in the MIS 6–7 interval and prior to 0.5 Ma for the deeper water sites [*Grützner et al.*, 2002]. The tuning was performed on one "reference" site from each group (Site 1058 and Site 1062), and the other sites in the group were correlated to these reference sites using the filtered and unfiltered carbonate proxy (reflectance) records.

[5] Planktic oxygen isotope data (from *Globigerinoides ruber*) are available for part of the MIS 1–6 interval at Hole 1063D [*Keigwin*, 2001]. A detailed benthic δ^{18}O record, based on *Cibicidoides wuellerstorfi*, is available for the MIS 11–12 interval [*Poli et al.*, 2000; *Thunell et al.*, 2002] and a mixed-species benthic record is available for the 260 to 340 ka interval [*Billups et al.*, 2011]. In addition, both benthic and plankic δ^{18}O are available at Site 1063 in the 730–1000 ka interval [*Ferretti et al.*, 2005]. The published oxygen isotope data at Site 1063 are too discontinuous to generate an isotopic age model for the site. We, therefore, used newly generated oxygen isotope data from *Globigerinoides ruber* to augment previously published δ^{18}O data (Figure 2), combined with relative paleointensity (RPI) data, to provide an alternative age model to that based on reflectance records by

Grützner et al. [2002]. *Keigwin and Jones* [1994] attributed changes in carbonate content of Bermuda Rise sediments in the MIS 1–4 interval to changes in North Atlantic Deep Water (NADW) production. It follows that carbonate percentage may not be simply related to orbital solutions.

2. Sampling

[6] U-channel samples were collected from the composite section of Site 1063, as defined shipboard [*Shipboard Scientific Party*, 1998], at the IODP core repository in Bremen. Due to previous sampling of the composite section, it was necessary to move the sampling from the composite section to Hole 1063D, in the 47–53 mcd and 135–144 mcd intervals, to complete sampling to the top of the Jaramillo Subchronozone at 188 mcd. After completion of magnetic measurements, the u-channels were completely sub-sampled (with IODP permission) into 5-cm-thick (20 cm^3) back-to-back aliquots for oxygen isotope analyses. Excursional paleomagnetic directions observed in u-channel data (Figure 3) were further investigated using 8 cm^3 cubic-shaped discrete samples from the same composite depth (mcd) in core sections from holes outside the u-channel section, or in some cases working from halves of the same core sections used for u-channel sampling.

3. Paleomagnetic (u-channel) Measurements

[7] Shipboard paleomagnetic measurements at Site 1063 comprised pass-through measurements of archive halves at 5-cm intervals using demagnetizing fields usually not exceeding 20 mT [*Shipboard Scientific Party*, 1998]. The maximum peak field was restricted so that core sections would not be compromised for shore-based magnetic investigations. Natural remanent magnetization (NRM) measurements of u-channel samples were made at 1-cm intervals, with a 10-cm leader and trailer at the top and base of each sample, using a 2-G Enterprises pass-through magnetometer at the University of Florida designed for the measurement of u-channel samples [e.g., *Weeks et al.*, 1993]. After initial NRM measurement of u-channel samples, stepwise AF demagnetization was carried out in 5 mT increments in the 20–60 mT interval and in 10 mT increments in the 60–100 mT interval using tracking speeds of 10 cm/s. Component magnetizations were computed for the 20–80 mT interval (Figure 3) using the standard least squares method [*Kirschvink*, 1980] without anchoring to the origin of the orthogonal projections, using UPmag software [*Xuan and Channell*, 2009]. The maximum angular deviation (MAD) values indicate variations in the quality of the component directions down-section with values generally below 5–10°, indicating well-defined magnetization directions (Figure 3) carried by a low-coercivity mineral, which is known from earlier studies in the region to be magnetite [e.g., *Schwartz et al.*, 1996; *Lund et al.*, 2005]. MAD values exceed 10° in some intervals, particularly close to the base of the sampled section and in the vicinity of apparent geomagnetic excursions. MAD values can be decreased by choosing individualized demagnetization ranges for individual stratigraphic levels or discrete stratigraphic intervals, however, determining MAD values for a global (20–80 mT) demagnetization range allows a more straightforward assessment of the quality of the directional record (Figure 3). MAD values are often >10° in the Matuyama Chron, indicating poorly defined magnetization components. The top of the Jaramillo Subchronozone is at 188 mcd, consistent with shipboard measurements [*Shipboard Scientific Party*, 1998]. Component declinations (Figure 3) were adjusted for vertical-axis core rotation by uniform rotation of each core such that the mean core declination is oriented North or South for positive and negative inclination intervals, respectively.

[8] In Figure 3, component inclination values determined from u-channel data (black) are compared with color-coded shipboard inclination data from half cores after demagnetization at a peak field of 20 mT [*Shipboard Scientific Party*, 1998]. Several intervals of negative component inclination in the u-channel data correspond to excursions from earlier studies of Site 1063 [*Lund et al.*, 1998, 2001a, 2001b]: Laschamp (3β), Blake (5β), Iceland Basin (7α) and Pringle Falls (7β) and the "Bermuda" excursion (11α), with the MIS-coded excursion labeling of *Lund et al.* [2001a, 2001b] given in brackets. The apparent "Bermuda" excursion at 412 ka (90.1 mcd) is poorly defined in the u-channel data, with MAD values exceeding 10°, shallow component inclinations and no apparent change in declination. Several apparent excursions in shipboard data (e.g., 3α and 5α of *Lund et al.* [2001a, 2001b]) are not observed as intervals of negative inclination in our u-channel record. Apparent magnetic excursions and accompanying discrete sample data are discussed in detail below (Section 6).

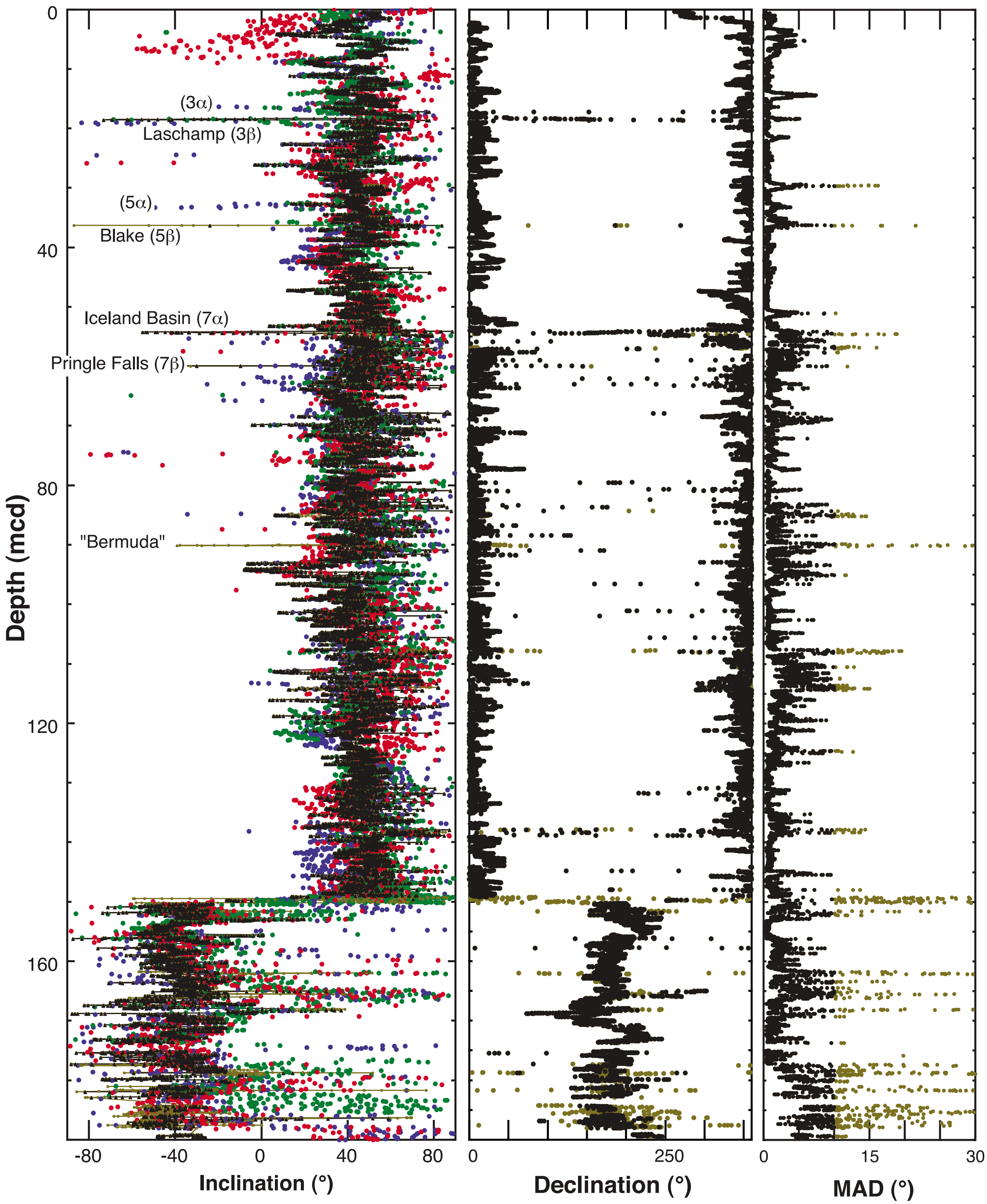

Figure 3. Black indicates Site 1063 u-channel component declination and inclination values with associated maximum angular deviation (MAD) values (for MAD < 10°) computed for the 20–80 mT demagnetization interval. Brown indicates u-channel data associated with MAD values >10° computed over the same demagnetization interval. In the inclination plot, red indicates Hole 1063A shipboard half-core data after demagnetization at a peak field of 20 mT, blue indicates Hole 1063C shipboard half-core data after demagnetization at a peak field of 20 mT, and green indicates Hole 1063D shipboard half-core data after demagnetization at a peak field of 20 mT.

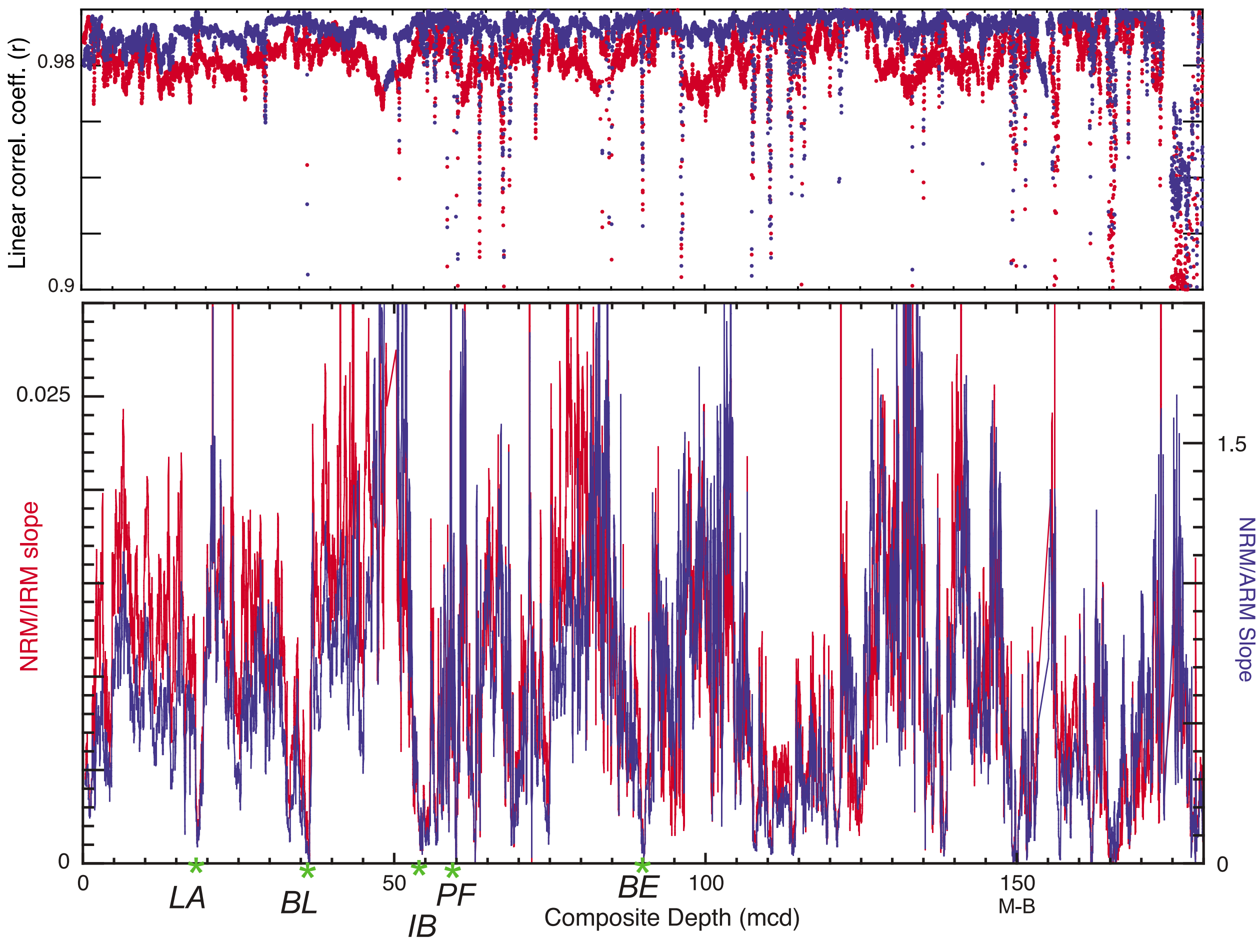

Figure 4. Paleointensity proxies. Slopes of NRM-lost versus ARM-lost (blue) and NRM-lost versus IRM-lost (red) in the 20–60 mT demagnetization interval, and their corresponding linear correlation coefficients (r), plotted versus meters composite depth (mcd). Paleointensity minima associated with the Laschamp (LA), Blake (BL), Iceland Basin (IB), Pringle Falls (PF) and "Bermuda" (BE) excursions are indicated by green stars. M-B indicates Matuyama-Brunhes boundary.

[9] Under favorable circumstances, the relative paleointensity (RPI) of the ancient magnetizing field can be determined from sediments using the ratio of NRM intensity to a normalizer sensitive to the concentration of remanence-carrying grains [*Banerjee and Mellema*, 1974; *Levi and Banerjee*, 1976; *King et al.*, 1983; *Tauxe*, 1993]. Anhysteretic remanent magnetization (ARM) and isothermal remanent magnetization (IRM) are laboratory-acquired magnetizations that are commonly used as normalizers. These artificial magnetizations activate slightly different grain size fractions of magnetite, with IRM being sensitive to coarser grains in the few-micron grain size range. Following *Channell et al.* [2002], we use the slopes of NRM/ARM and NRM/IRM in the 20–60 mT demagnetization interval as RPI proxies, with associated linear correlation coefficients (r) as a measure of data quality (Figure 4). The two RPI proxies at Site 1063 are broadly consistent, which gives us confidence in the RPI record, and the linear correlation coefficients (r) are close to unity which indicates that the slopes are reasonably well defined within this (20–60 mT) demagnetization interval. The NRM/IRM record is associated with many of the r-values below 0.98, probably due to the greater effect of coarse magnetite grains (that do not contribute significantly to NRM) on IRM relative to ARM.

4. Oxygen Isotope Measurements

[10] Due to the discontinuous presence of benthic foraminifera in the Quaternary section at Site 1063, the planktic foraminifer *Globigerinoides ruber* was used for oxygen isotope analyses due to its continuous presence in the upper 170 mcd (Figure 2).

Specimens were picked from the >212 μm size fraction from the 20 cm^3 sample representing each 5-cm of core section. In general, three to eight individuals (20–55 μg) were used for analysis. Foraminifer tests were soaked in ~15% H_2O_2 for 30 min to remove organic matter. The tests were then rinsed with methanol and ultrasonically cleaned to remove fine-grained particles. The methanol was removed with a syringe, and samples were dried in an oven at 50°C for 24 h. The foraminifer calcite was loaded into individual reaction vessels, and each sample was reacted with three drops of H_3PO_4 (specific gravity = 1.92) using a Finnigan MAT Kiel III carbonate preparation device. Isotope ratios were measured online by a Finnigan MAT 252 mass spectrometer. Analytical precision was estimated to be 0.08‰ for δ^{18}O and 0.04‰ for δ^{13}C by measuring eight standards (NBS-19) with each set of 38 samples. A total of 3070 samples of *Globigerinoides ruber* were measured at the University of Florida for this study. These planktic δ^{18}O data are augmented by previously published δ^{18}O studies on sediments from Site 1063: a mixed-species benthic δ^{18}O record in MIS 8–9 [*Billups et al.*, 2011], benthic δ^{18}O in the MIS 11–12 interval using *Fontbotia wuellerstorfi* [*Poli et al.*, 2000; *Thunell et al.*, 2002], and δ^{18}O in the 143–194 mcd (MIS18–28) interval using the planktic species *Globorotalia inflata* and the benthic foraminifera *Cibicides wuellerstorfi* or *Nuttallides umbonifera* [*Ferretti et al.*, 2005]. On Bermuda Rise, the δ^{18}O values from *Globorotalia inflata* and *Globigerinoides ruber* have been found to yield consistent δ^{18}O values [*Keigwin and Jones*, 1994]. At Site 1063, decreases in δ^{18}O at glacial terminations are synchronous where both planktic and benthic data exist (Figure 2), thereby lending confidence in the correlation of age tie points to a benthic δ^{18}O reference template (LR04 [*Lisiecki and Raymo*, 2005]). At high latitude sites, planktic δ^{18}O often leads benthic δ^{18}O at terminations because of the presence of low-δ^{18}O glacial meltwater. Planktic δ^{18}O records on the Bermuda Rise are marked by millennial-scale variability [*Keigwin and Jones*, 1994; *Ferretti et al.*, 2005]. To facilitate correlation to the LR04 benthic δ^{18}O stack, we use a 5-pt running mean of the planktic δ^{18}O data (Figure 2).

5. Age Model

[11] An age model for the Site 1063 was constructed by tandem fitting of δ^{18}O and RPI to the following reference curves: the "PISO" RPI stack [*Channell et al.*, 2009] and the LR04 benthic δ^{18}O stack [*Lisiecki and Raymo*, 2005]. The tandem correlations were performed using the *Match* protocol [*Lisiecki and Lisiecki*, 2002] that can be used to optimize correlations of pairs of ostensibly independent signals (δ^{18}O and RPI) [see *Channell et al.*, 2009]. The advantage of *Match* over visual matching is that *Match* correlations are based on firm criteria and are repeatable which is not the case for visual correlations, particularly visual correlations involving independent pairs of signals. *Match* is adjustable to the series under consideration by introduction of penalty functions that minimize the likelihood of sedimentation rate changes within and between time/depth series.

[12] Our procedure for generating the Site 1063 age model is as follows: (1) tandem *visual* correlation of the δ^{18}O record to LR04, and the RPI record to the PISO stack, using 43 tie points, (2) application of *Match* to improve and optimize correlation of the δ^{18}O and RPI records to the LR04 and PISO stacks, and (3) comparison of correlation coefficients for the visual and *Match* correlations. Both δ^{18}O and RPI correlation coefficients indicate that the *Match* correlation is an improvement over the visual correlation.

[13] In Figure 5, the Site 1063 benthic and planktic δ^{18}O records, on the age model described here, are compared with the LR04 benthic δ^{18}O stack, and the Site 1063 RPI record, on the same age model, is shown together with the PISO reference stack. Both the δ^{18}O and RPI records can be matched to the calibrated templates to provide an internally consistent age model (Figure 5), although the Site 1063 RPI record is suppressed relative to the reference template in the 500–620 ka interval. The resulting Site 1063 sedimentation rates are shown in Figure 6, together with sedimentation rates from *Grützner et al.* [2002]. For comparison of age models, the planktic δ^{18}O record in Figure 6 is placed both on the age model presented here and on the alternative age model of *Grützner et al.* [2002].

6. Geomagnetic Excursions

[14] The use of 8 cm^3 discrete sample cubes helps to confirm the existence of geomagnetic excursions recognized from u-channel data and to determine the stratigraphic thickness over which the excursions are recorded in order to estimate excursion duration. Although u-channel magnetic measurements were made at 1-cm intervals, measurements at this spacing are not independent due to the ~4.5 cm wide Gaussian-shaped response

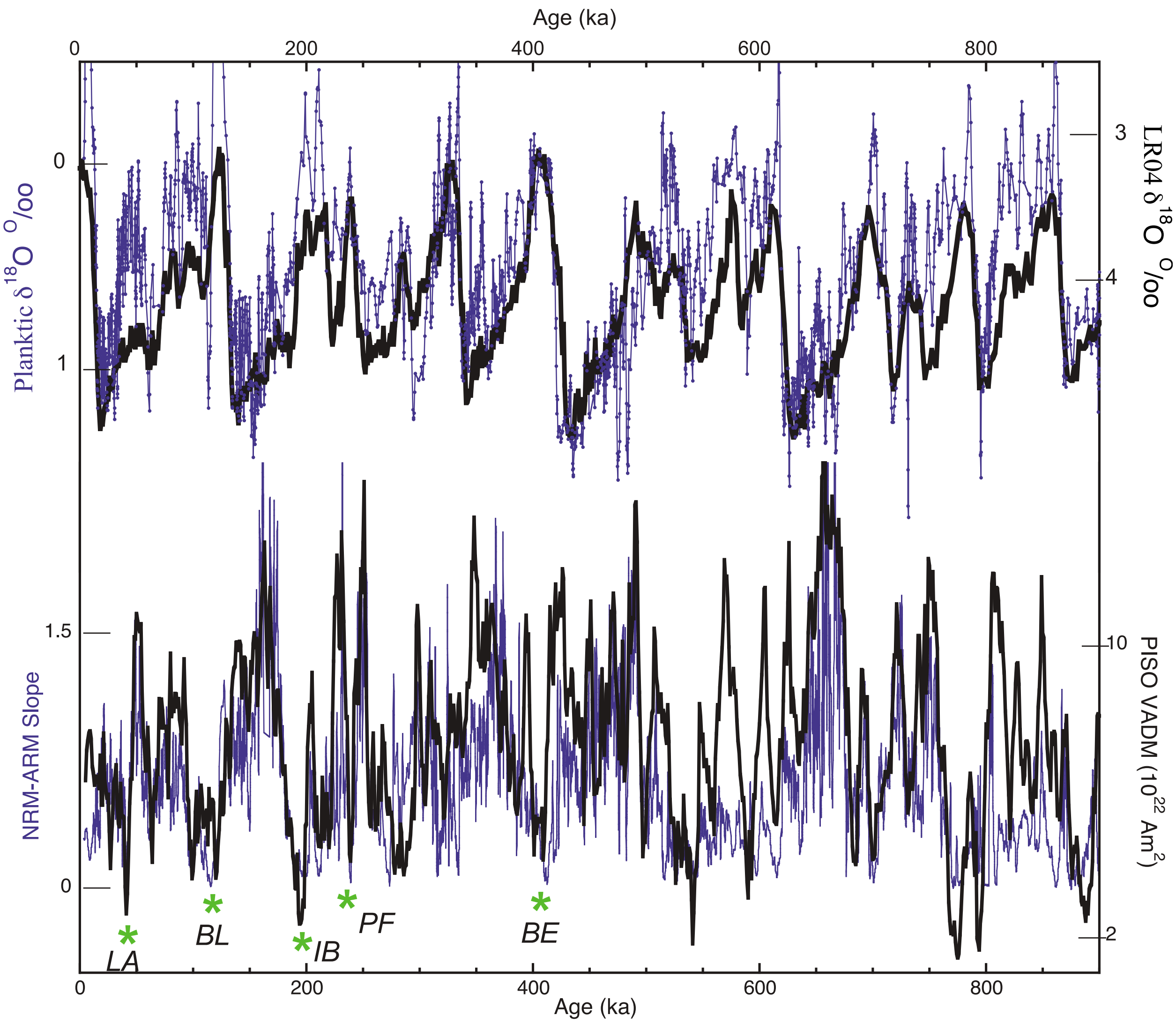

Figure 5. (top) Site 1063 planktic δ^{18}O from this study on the age model presented here (blue), smoothed with a 5-point running mean, and compared with a calibrated template (black) (LR04 [*Lisiecki and Raymo*, 2005]). (bottom) Site 1063 paleointensity proxy (slope of NRM/ARM) on the age model presented here (blue), compared with the PISO paleointensity template (black) [*Channell et al.*, 2009]. Paleointensity minima associated with Laschamp (LA), Blake (BL), Iceland Basin (IB), Pringle Falls (PF) and "Bermuda" (BE) excursions are indicated by green stars. Matuyama-Brunhes boundary is marked by the younger of two paleointensity minima at ~775 ka.

function of the magnetometer [*Weeks et al.*, 1993; *Guyodo et al.*, 2002]. Discrete samples were AF demagnetized in 5 mT steps in the 10–100 mT peak-field range. The demagnetization data are then displayed as orthogonal projections and compared with the u-channel data.

[15] *Lund et al.* [2001a] recognized Excursion 3α, which is possibly equivalent to the Mono Lake Excursion, at several ODP Leg 172 sites, in the shipboard data for Holes 1063C and 1063D but not in shore-based u-channel records from Site 1063. Similarly, we do not see evidence for this excursion in our u-channel records (Figure 3). The Mono Lake excursion has its origin in the Great Basin of western North America, particularly at the "type" section at Mono Lake [*Liddicoat and Coe*, 1979; *Negrini et al.*, 1984; *Liddicoat*, 1992].

[16] Until about a decade ago, records of the Laschamp Excursion were restricted to volcanic records from France [*Bonhommet and Babkine*, 1967; *Bonhommet and Zahringer*, 1969]. The excursion has now been observed in cores with robust age control over a large part of the North Atlantic and Gulf of Mexico [*Laj et al.*, 2000, 2006;

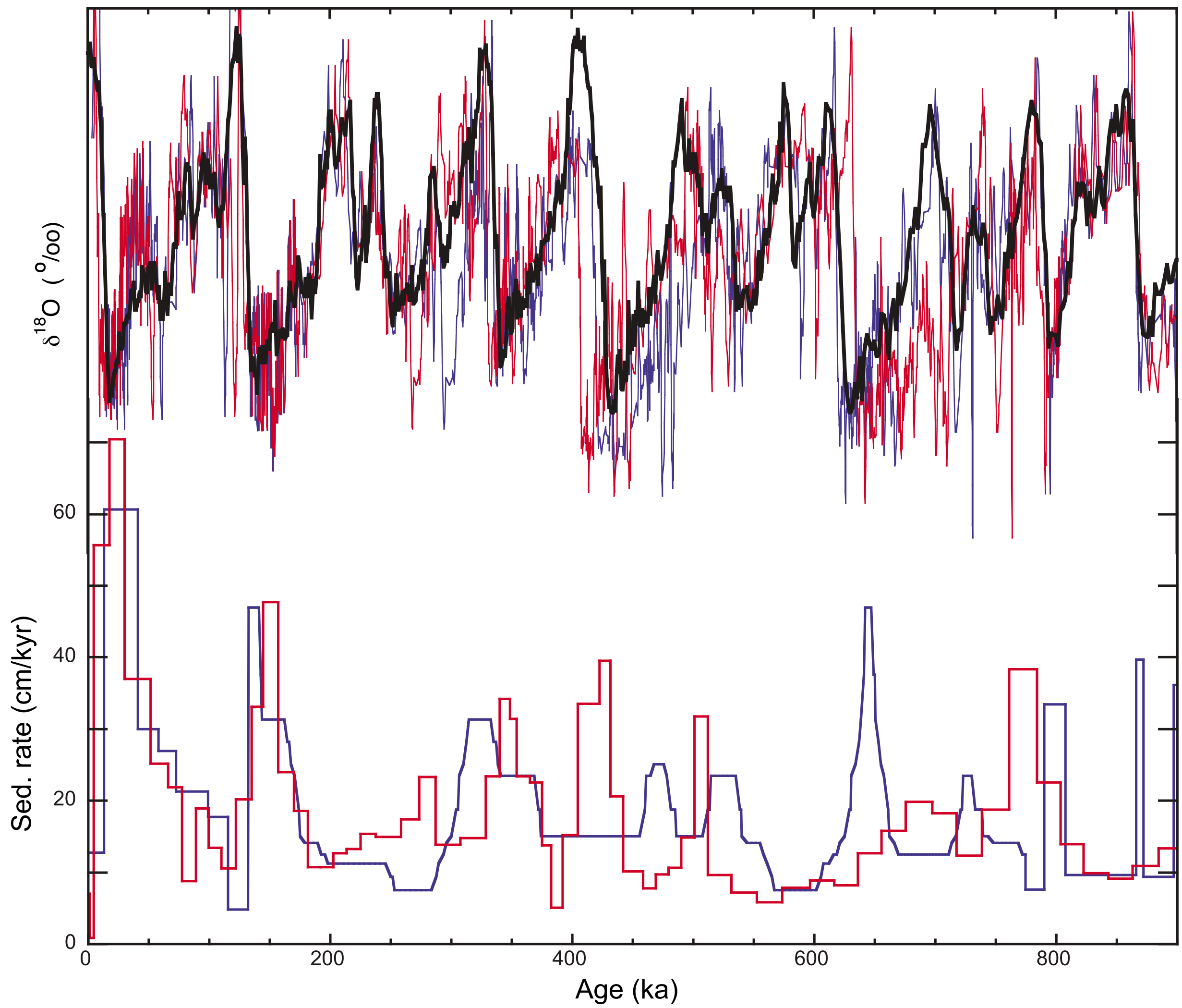

Figure 6. Planktic $\delta^{18}O$ from this study (blue) and LR04 (black [*Lisiecki and Raymo*, 2005]) with sedimentation rates according to the age model adopted here (blue), and $\delta^{18}O$ and sedimentation rates according to the age model of *Grützner et al.* [2002] (red).

Lund et al., 2005; *Evans et al.*, 2007], in several southern ocean cores [*Channell et al.*, 2000; *Mazaud et al.*, 2002; *Laj et al.*, 2006] and in multiple volcanic records [*Guillou et al.*, 2004; *Cassidy*, 2006; *Cassata et al.*, 2008; *Singer et al.*, 2009]. The excursion is recorded at Site 1063 in both shipboard and u-channel data (Figure 3). In the terminology of *Lund et al.* [2001a], this is Excursion 3β. An enlarged look at the u-channel record (core section 1063C-3H-3) demonstrates that the Laschamp excursion is recorded by well-defined magnetization components (low MAD values) indicating paired "reversals" bracketing reversed polarity virtual geomagnetic poles (VGPs) (Figure 7). Discrete samples also record the excursion at closely equivalent composite depths in two additional core sections (1063A-3H-2 and 1063D-3H-5) (Figure 8). Orthogonal projections of AF demagnetization data for discrete samples indicate that excursional magnetization directions are manifested over about 10–20 cm in each core section, corresponding to an estimated duration of ~0.5 kyr for the Laschamp excursion (Table 1). The stratigraphic thickness associated with excursional directions, defined here as directions outside the range of expected secular variation, can be difficult to estimate as the amplitude of "expected" secular variation is somewhat subjective. The estimated age of the Laschamp excursion (41 ka) is consistent with radiometric dates for the excursion in volcanic flows in the Puy de Laschamp of the Massif Central, France [*Guillou et al.*, 2004; *Singer et al.*, 2009]. Note that in the comparison of u-channel and discrete sample data for Site 1063

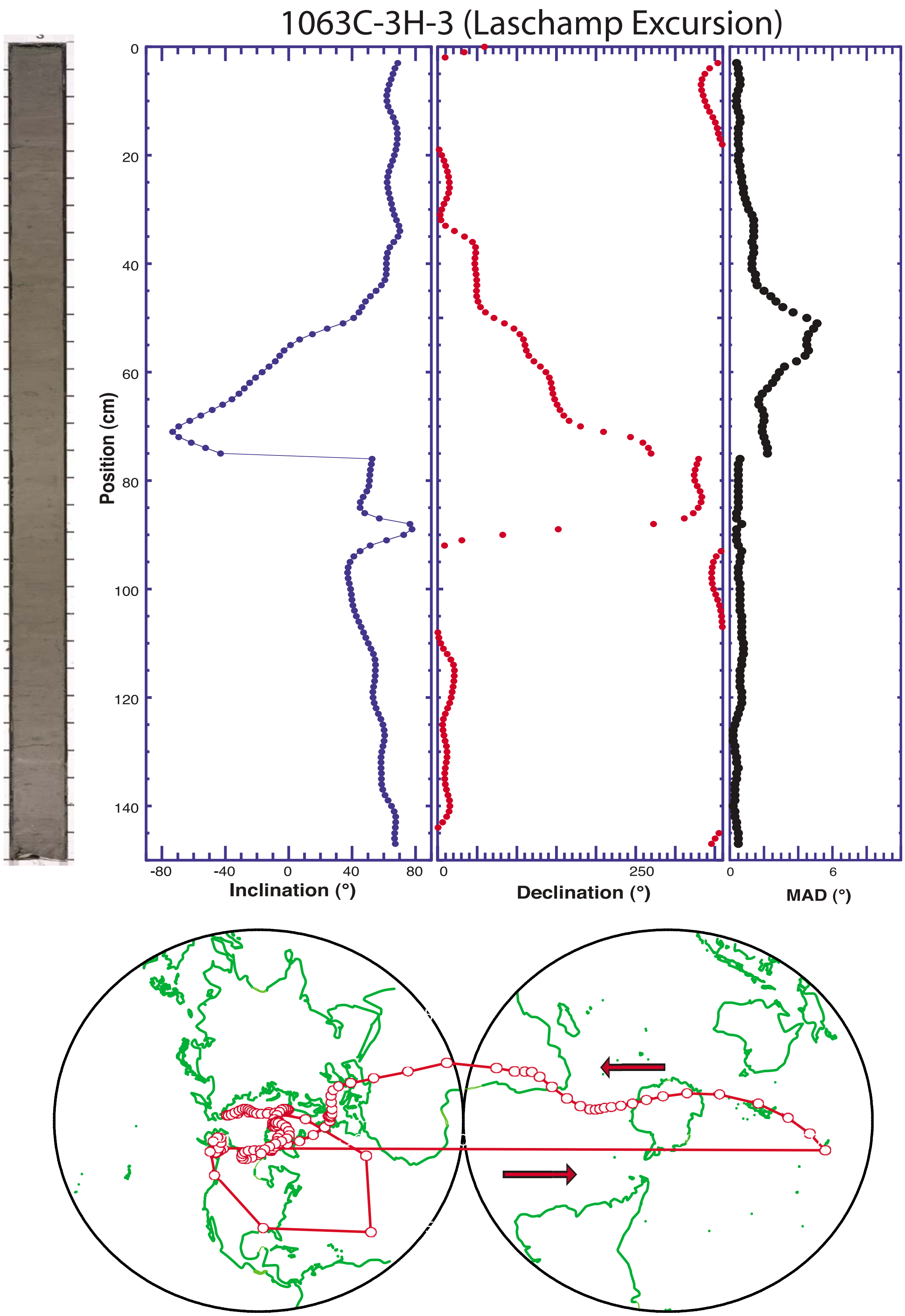

Figure 7. U-channel record of the Laschamp excursion from Hole 1063C. Component magnetization directions with maximum angular deviation (MAD) values determined for the 20–80 mT demagnetization interval yielding virtual geomagnetic poles (VGPs) that reach high southern latitudes.

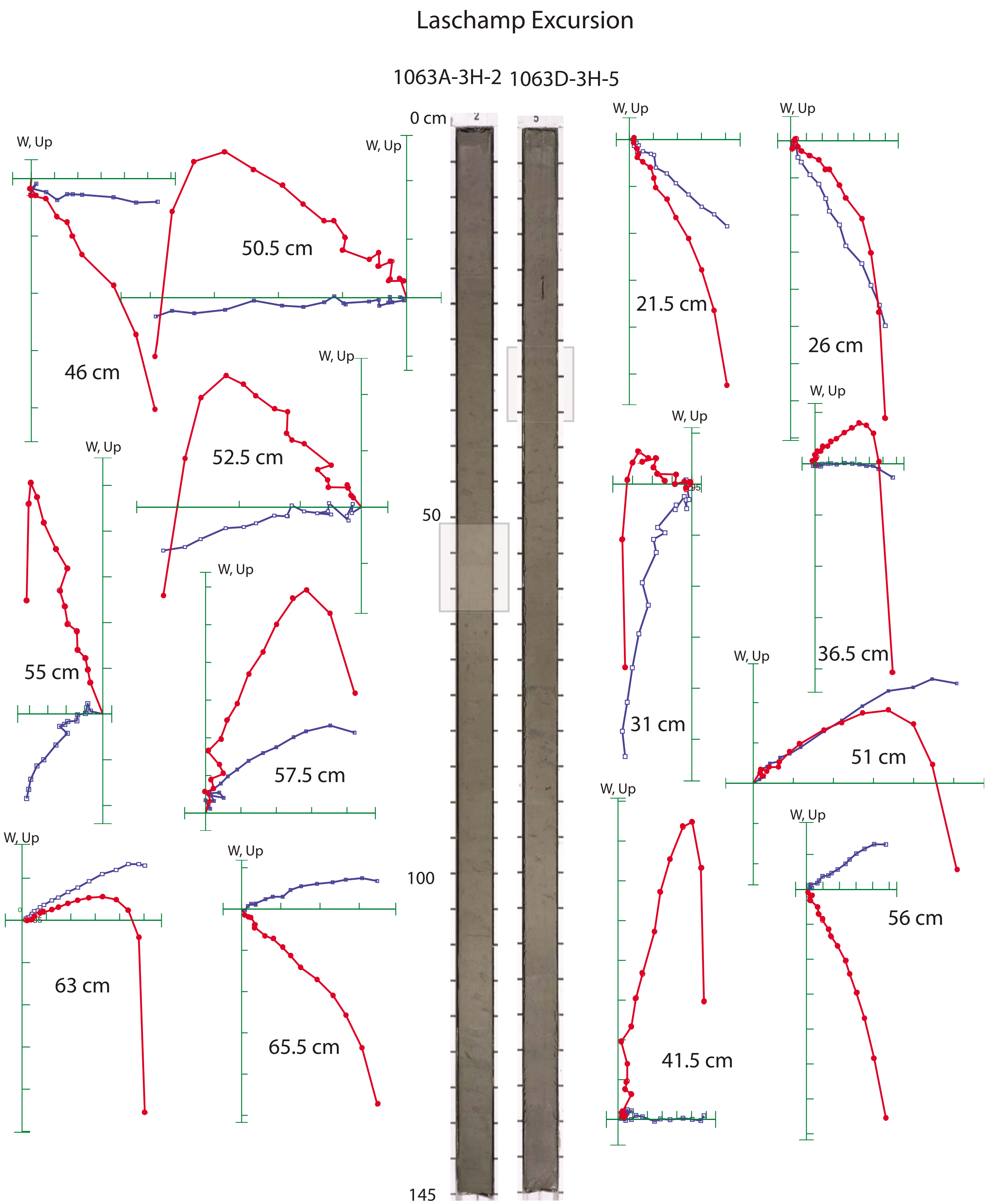

Figure 8. Orthogonal projections of AF demagnetization data for discrete (8 cm^3) samples that record the Laschamp excursion in sections from Holes 1063A and 1063D. The cm-level in the section is shown for each sample. Red (blue) symbols represent projections onto the vertical (horizontal) planes. The range of peak field demagnetization for each plot is 10–80 mT. Note that declinations in orthogonal projections are not rotated as for the u-channel data in Figure 7. Shaded boxes indicate intervals with negative component inclinations.

Table 1. Position, Marine Isotope Stage, Age, Stratigraphic Thickness and Duration for Likely Excursions Recorded at ODP Site 1063[a]

Excursion[b]	Cat	mcd (midpoint)	MIS	Age (ka)	Thickness (cm)	Sedimentation Rate (cm/kyr)	Duration (kyr)
Laschamp (3β)	1	18.47	3	40.8	~20	44	~0.5
Blake (5β)	1	36.32	5d/5e	115.5	~10	11.5	~0.9
Iceland Basin (7α)	1	54.25	6/7	189.7	~20	14	~1.4
Pringle Falls (7β)	1	59.92	7	238.8	~10	11.3	~0.9
"Bermuda" (11β)	2	90.09	11	412.4	~10	15	~0.7
"318 ka" (9α)	2	69.77	9	318.1	~20	31.2	~0.6
"530 ka" (13α)	2	111.25	14	529.6	~40	23.6	~1.7
"557 ka"	2	116.03	14/15	557.3	~15	13.5	~1.1

[a]Abbreviations: Cat, Category; mcd, meters composite depth; MIS, Marine Isotope Stage.
[b]Terminology of *Lund et al.* [2001a, 2001b] is in parentheses.

excursions (e.g., Figures 7 and 8), u-channel declinations are "corrected," as described above, and discrete sample declinations are arbitrary as there is no basis for imposing a declination corrections on cores outside the u-channel (composite) section.

[17] The Blake Excursion has apparently been recorded as a single reverse polarity zone [*Tucholka et al.*, 1987], as two reverse polarity zones [*Creer et al.*, 1980; *Tric et al.*, 1991; *Fang et al.*, 1997] and as three reverse polarity zones [*Denham*, 1976; *Zhu et al.*, 1994] in records from the Mediterranean Sea, western Atlantic Ocean and Chinese loess. The excursion occurs in marine isotope stage (MIS) 5, in the vicinity of the MIS 5e/5d boundary [*Tric et al.*, 1991]. In the Site 1063 u-channel record, the Blake excursion is recorded in Hole 1063B over about 10 cm of core, yielding high latitude southerly VGPs flanked by a pair of reversals, within a short stratigraphic interval corresponding to the MIS 5d/5e boundary (Figures 3 and 9). This excursion is equivalent to Excursion 5β of *Lund et al.* [2001b]. We do not observe Excursion 5α of *Lund et al.* [2001b] in the u-channel record, although corresponding excursional directions are observed in shipboard data at Holes 1063C and 1063D (Figure 3). Discrete samples collected from Hole 1063B indicate excursional directions corresponding to the Blake excursion over about 10 cm of core (Figure 10), which implies an excursional duration of <1 kyr at 116 ka (Table 1).

[18] The Iceland Basin Excursion at ~188 ka observed in the Iceland Basin and Rockall Bank [*Channell et al.*, 1997; *Channell*, 1999; *Channell and Raymo*, 2003] is apparently coeval with excursions elsewhere in the central North Atlantic Ocean [*Weeks et al.*, 1995; *Lehman et al.*, 1996] as well as in the western equatorial Pacific [*Yamazaki and Ioka*, 1994], South China Sea [*Laj et al.*, 2006], North Pacific [*Roberts et al.*, 1997], South Atlantic [*Stoner et al.*, 2003] and in Lake Baikal [*Oda et al.*, 2002]. This excursion has been documented over a large portion of the globe, and can be correlated to the MIS 7/6 boundary. In the u-channel data from Hole 1063B, it occurs over ~20 cm of section and yields high-latitude southerly VGPs implying paired reversals of the Earth's main dipole (Figure 11). This excursion is equivalent to Excursion 7α of *Lund et al.* [2001b]. Discrete samples collected from Hole 1063A and Hole 1063B provide further definition of the excursion [*Knudsen et al.*, 2006]. In our discrete sample record, the excursion is recorded over about 20–30 cm of core spanning two sections (Figure 12) consistent with the results of *Knudsen et al.* [2006], implying an excursional duration of ~1.5 kyr at 190 ka (Table 1). We estimate that the sedimentation rate across the Iceland Basin excursion was ~14 cm/kyr (Figure 6). *Knudsen et al.* [2007] used excess ^{230}Th to estimate a mean sedimentation rate in the 10–15 cm/kyr range across the Iceland Basin excursion at Site 1063, similar to the values estimated here, but determined a duration of 7–8 kyr for the excursion. Their duration estimate is at odds with the estimate given here, but is entirely explicable in terms of the definition of the onset/end of the excursional interval. Defining the excursion as bounded by first and last VGP latitudes <45° *immediately before and after* negative VGP latitudes, from their data, we get a duration ~30% of *Knudsen et al.*'s [2007] estimate. *Knudsen et al.* [2007] choose to define the excursion as bounded by first and last VGP latitudes <45° over a wider stratigraphic interval [see *Knudsen et al.*, 2007, Figure 1c].

[19] The Pringle Falls Excursion was first documented in lacustrine sediments that crop out in Oregon near Pringle Falls [*Herrero-Bervera et al.*,

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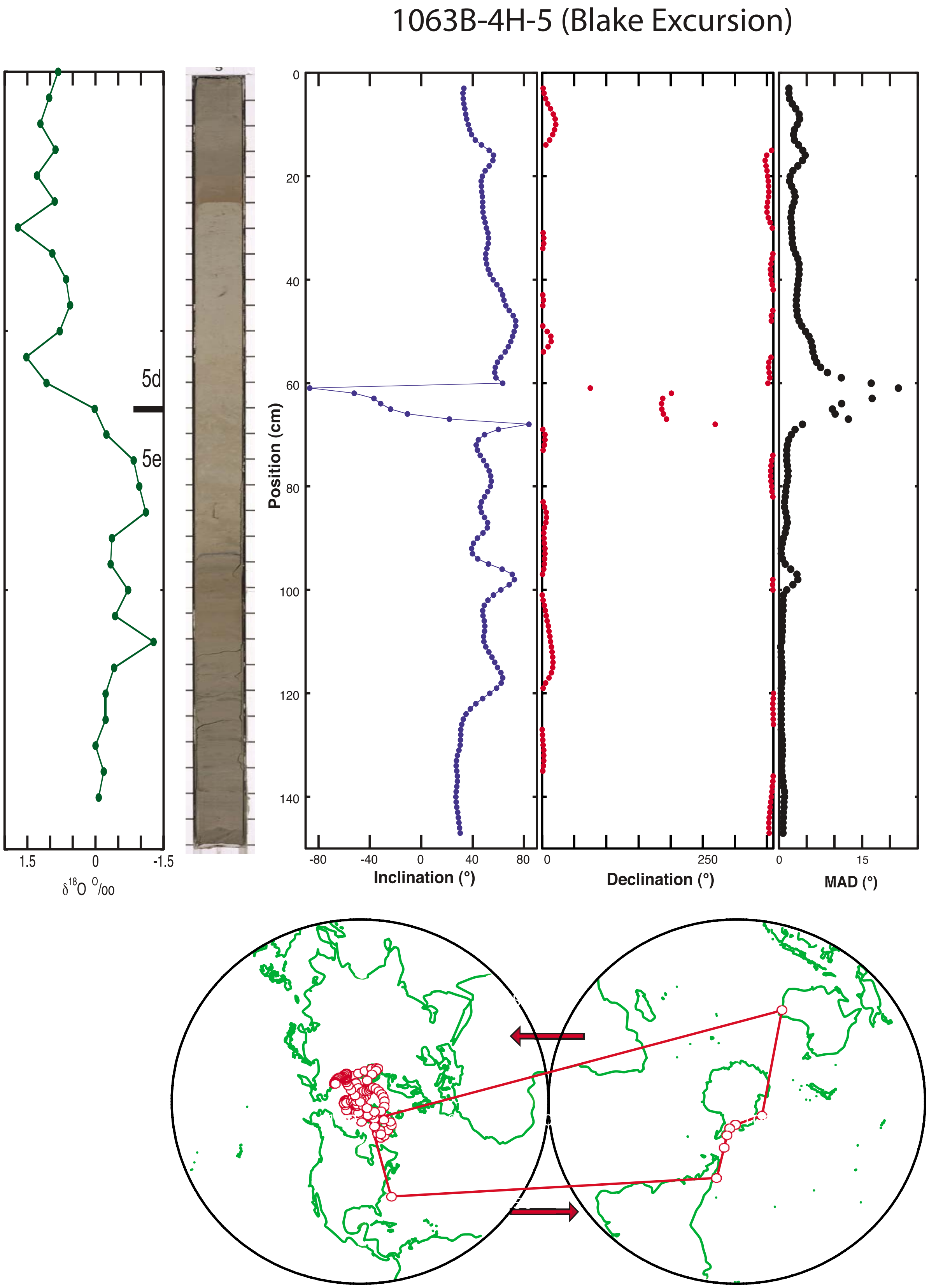

Figure 9. U-channel record of the Blake excursion from Hole 1063B. Component magnetization directions with maximum angular deviation (MAD) values determined for the 20–80 mT demagnetization interval yielding virtual geomagnetic poles (VGPs) that reach high southern latitudes.

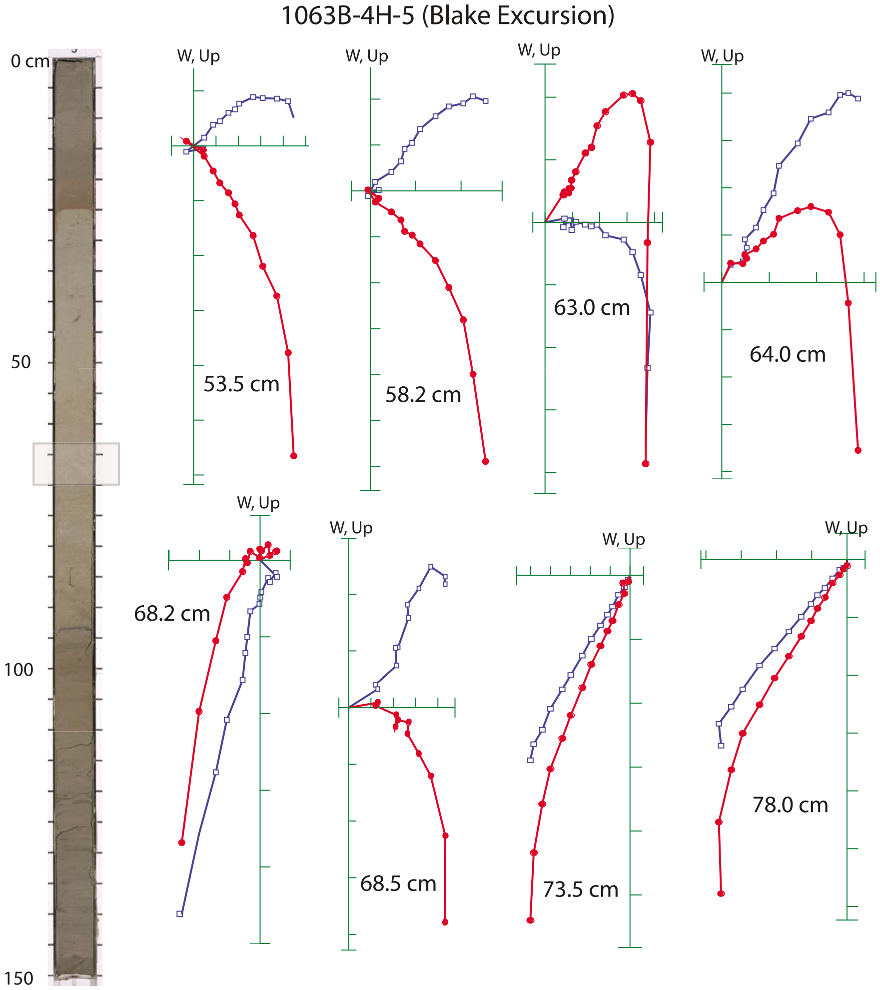

Figure 10. Orthogonal projections of AF demagnetization data for discrete (8 cm^3) samples that record the Blake excursion in Hole 1063B. The cm-level in the section is shown for each sample. Red (blue) symbols represent projections onto the vertical (horizontal) planes. The range of peak field demagnetization for each plot is 10–80 mT. Note that declinations in the orthogonal projections are not rotated as for the u-channel data in Figure 9. The shaded box indicates the interval with negative component inclinations.

1989, 1994], at nearby Summer Lake [*Negrini et al.*, 1994] and in Long Valley, California [*Liddicoat et al.*, 1998]. Regional tephrochronology yields age estimates close to 220 ka [*Herrero-Bervera et al.*, 1994; *Liddicoat et al.*, 1998]. *McWilliams* [2001] gave an $^{40}Ar/^{39}Ar$ age of 223 ± 4 ka for the Mamaku ignimbrite in New Zealand that carries excursional magnetization directions [*Shane et al.*, 1994]. A recent study has equated the Pringle Falls Excursion with an excursion recorded in the Albuquerque Volcanics that has a younger $^{40}Ar/^{39}Ar$ age of 211 ± 13 ka [*Singer et al.*, 2008a]. Results from Site 1063 indicate a possible representation of the Pringle Falls excursion at ~238 ka in MIS 7, distinct in age from the Iceland Basin Event at ~190 ka near the MIS 7/6 boundary (Figure 5). The u-channel record appears to exhibit the Pringle Falls Excursion over about 10 cm of section in Hole 1063C, and the excursion is represented by high southerly latitude VGPs (Figure 13). This excursion is equivalent to Excursion 7β of *Lund et al.* [2001b]. Discrete samples from Hole 1063D record excursional directions over less than 10 cm of core at an equivalent composite depth (Figure 14).

[20] Prior to the Pringle Falls Excursion (Figure 3), there is only a single interval with negative inclinations in the u-channel record at 90 mcd (412 ka) in early MIS 11. At this level, u-channel data from Hole 1063C indicate negative component inclinations, but high MAD values indicate that these directions are poorly defined (Figure 15). This apparent excursion is equivalent to Excursion 11β

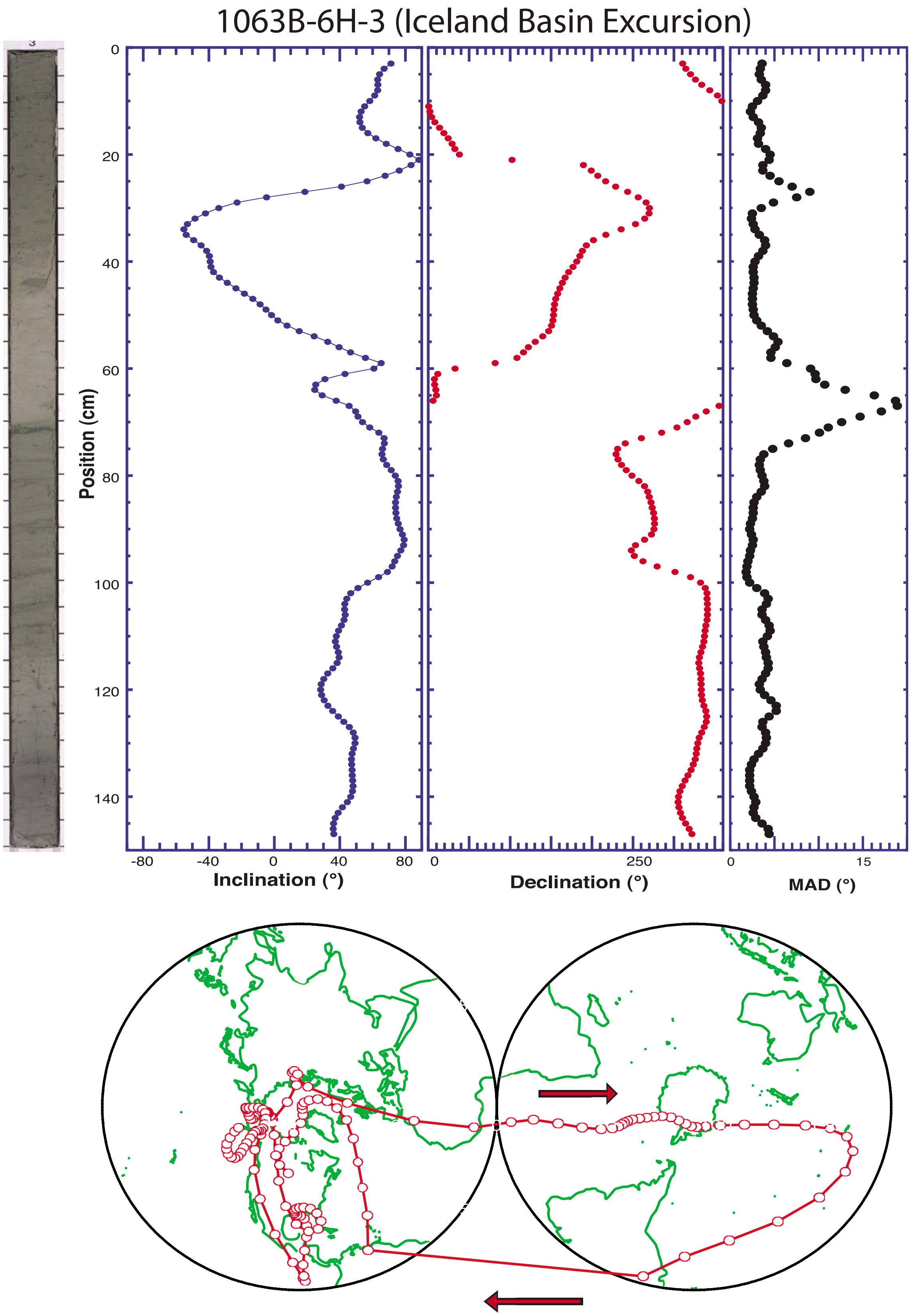

Figure 11. U-channel record of the Iceland Basin excursion in Hole 1063B. Component magnetization directions with maximum angular deviation (MAD) values determined for the 20–80 mT demagnetization interval yielding virtual geomagnetic poles (VGPs) that reach high southern latitudes.

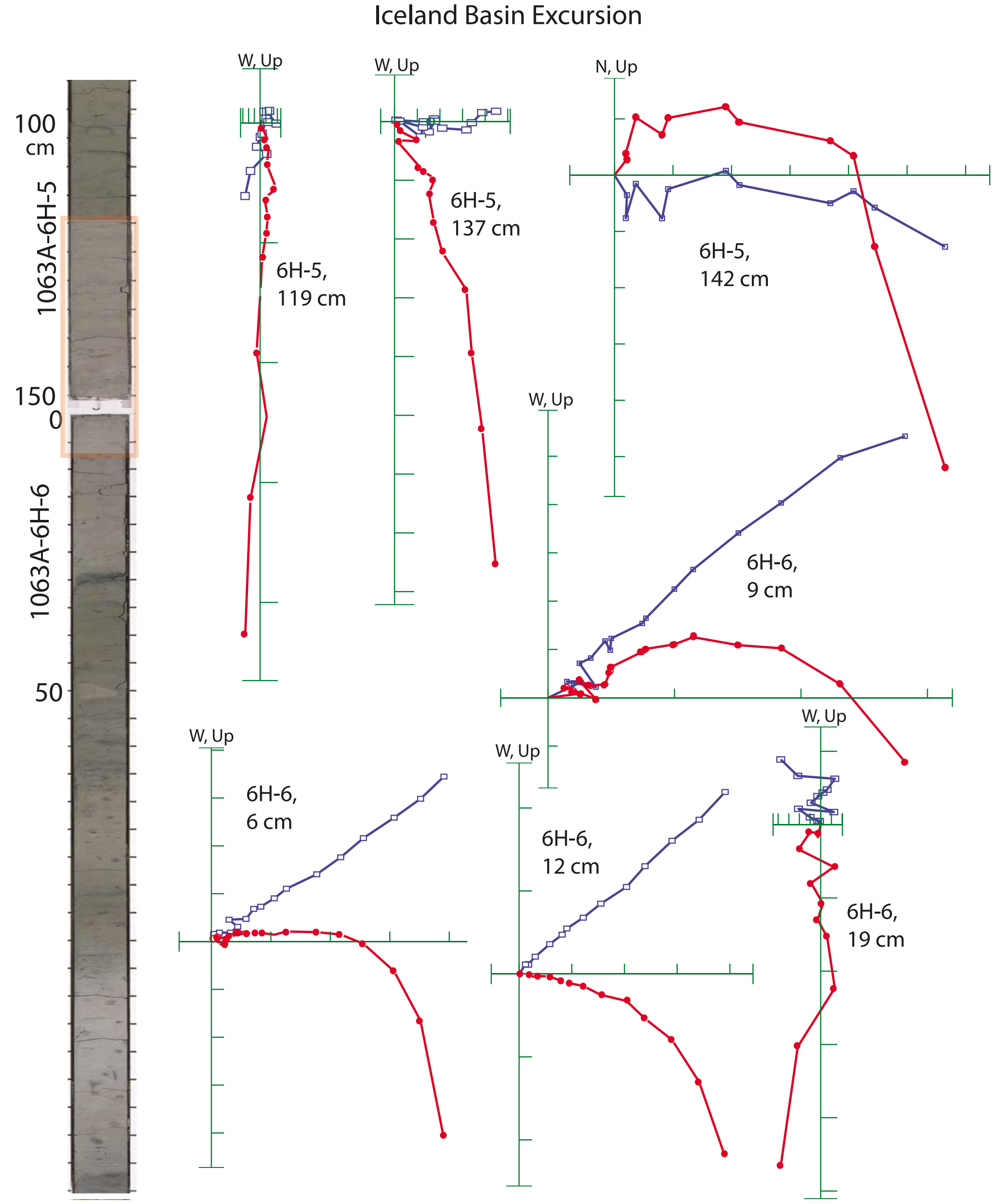

Figure 12. Orthogonal projections of AF demagnetization data for discrete (8 cm^3) samples that record the Iceland Basin excursion in Hole 1063A. The cm-level in the section is shown for each sample. Red (blue) symbols represent projections onto the vertical (horizontal) planes. The range of peak field demagnetization for each plot is 10–80 mT. Note that declinations in the orthogonal projections are not rotated as for the u-channel data in Figure 11. The shaded box indicates the interval with negative component inclinations that spans two core sections.

of *Lund et al.* [2001b], however, there is no apparent shift in declination associated with this excursional record, and VGP latitudes do not reach into the southern hemisphere (Figure 15). Discrete sample data collected at the same stratigraphic level in Hole 1063D have shallow inclinations (Figure 16) over ~10 cm of core implying millennial-scale duration for an apparent excursion, here coined the “Bermuda” excursion (Table 1).

[21] Other intervals with anomalous magnetization directions at Site 1063 (Figure 3) are manifest in the 65–80 mcd (MIS 8–10) interval (Figure 17). Shallow negative component inclinations are observed in u-channel data at ~70 mcd (~318 ka). This interval is equivalent to Excursion 9α of *Lund et al.* [2001b]. Excursion 9β of *Lund et al.* [2001b] appears in shipboard data from Holes 1063A and 1063C but not in the u-channel record (Figure 17)

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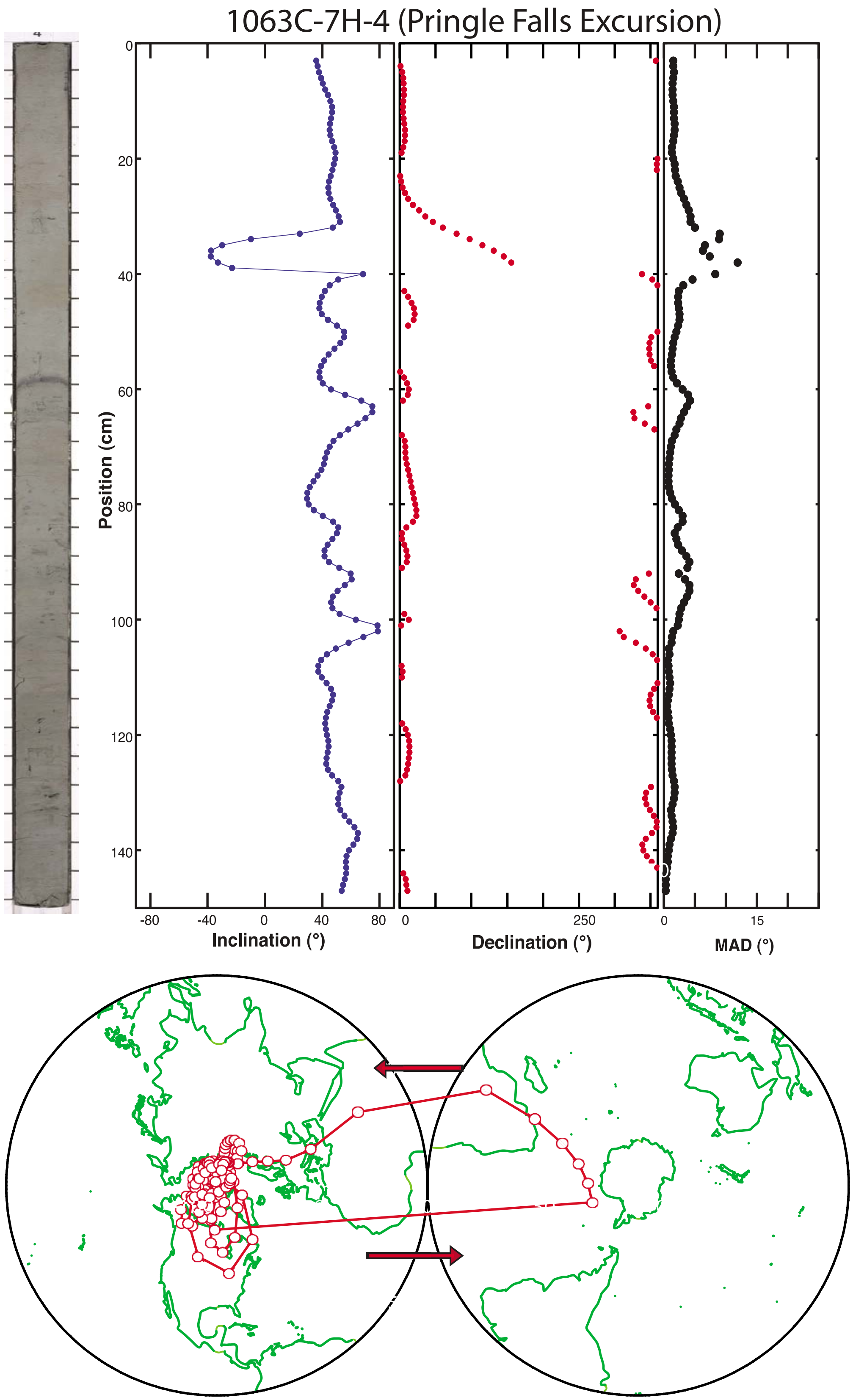

Figure 13. U-channel record of the Pringle Falls excursion in Hole 1063C. Component magnetization directions with maximum angular deviation (MAD) values determined for the 20–80 mT demagnetization interval yielding virtual geomagnetic poles (VGPs) that reach high southern latitudes.

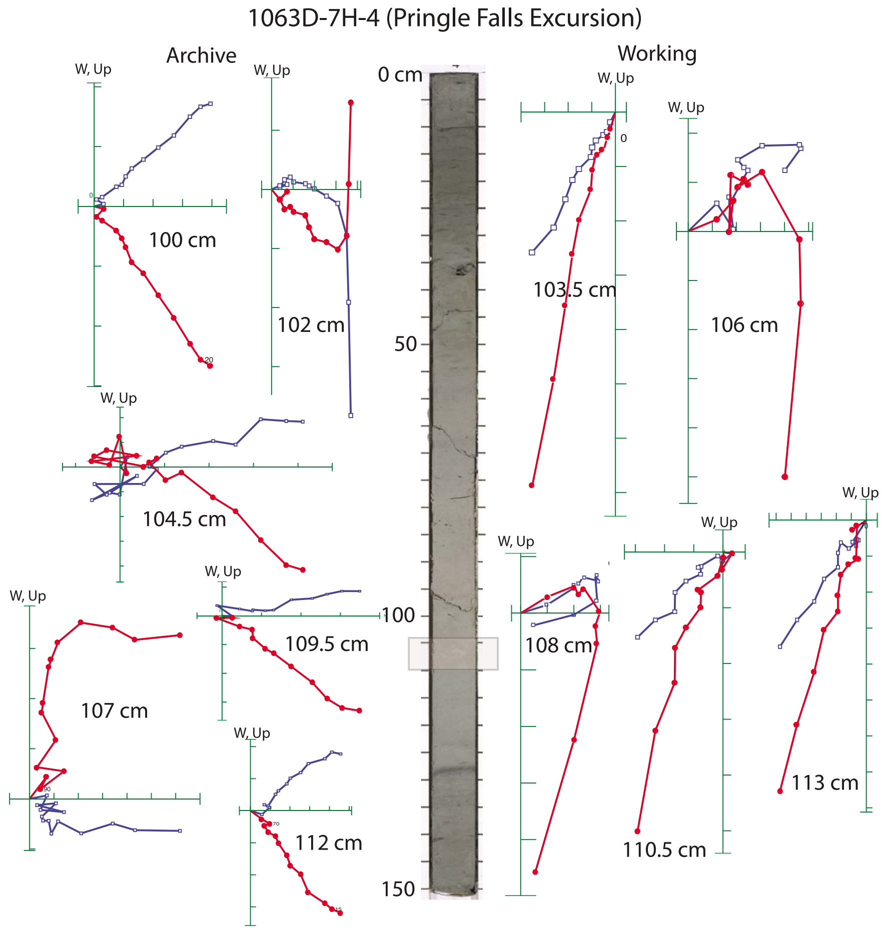

Figure 14. Orthogonal projections of AF demagnetization data for discrete (8 cm^3) samples that record the Pringle Falls excursion in Hole 1063D. The cm-level in the section is shown for each sample. Red (blue) symbols represent projections onto the vertical (horizontal) planes. The range of peak field demagnetization for each plot is 10–80 mT. Note that declinations in the orthogonal projections are not rotated as for the u-channel data in Figure 13. The shaded box indicates the interval with negative component inclinations.

that is from Hole 1063C in this interval. Discrete samples collected from Hole 1063D, at an equivalent composite depth, indicate shallowing of the component inclination in the 55–62 cm interval of Section 1063D-8H-4 (Figure 18), but provide no evidence for negative inclinations similar to those associated with younger excursions recorded at Site 1063.

[22] In the 110–120 mcd (500–600 ka) interval, there are several intervals with shallow inclinations in the u-channel record (Figure 19). One of these, close to the MIS 14/13 boundary (Termination VI) at ~111.0–111.5 mcd, is equivalent to Excursion 13α of *Lund et al.* [2001b]. This low inclination interval appears in shipboard data from Holes 1063A, 1063C and 1063D (Figure 3), and in the u-channel record that is derived from Hole 1063C in this interval (Figure 19). Component inclinations become shallow but remain positive with no declination change in this interval, and MAD values are low indicating that component magnetizations are well defined. Discrete samples collected from Hole 1063A have component inclinations as low as 7° at 111.2 mcd (not shown here), compatible with the low inclinations in the u-channel record (Figure 19). Excursion 14α of *Lund et al.* [2001b] is recorded in shipboard data from Hole 1063C (Figure 19) and in u-channel records also from Hole 1063C [*Lund et al.*, 2001b, Figure F5]. It is not recorded in the u-channel record reported here, where the record in this interval comes from Hole 1063B (Figure 19).

[23] Discrete samples have also been collected across two other intervals with shallow inclinations in the u-channel record at 557 ka (116 mcd) and 588–592 ka (~119 mcd) (Figure 19). In both

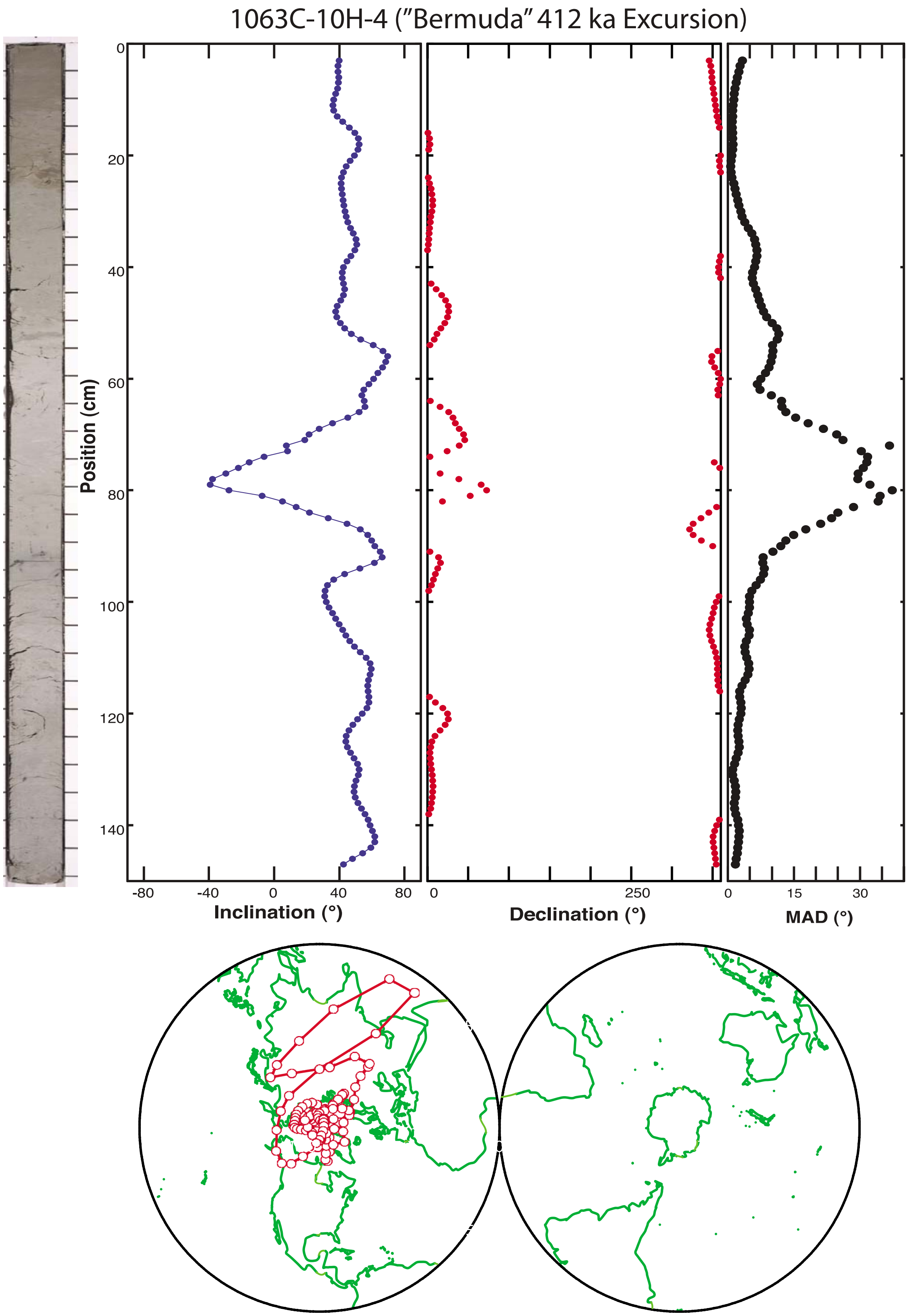

Figure 15. U-channel record of the "Bermuda" (412 ka) excursion in Hole 1063C. Component magnetization directions with maximum angular deviation (MAD) values determined for the 20–80 mT demagnetization interval. High MAD values indicate poorly defined component magnetizations. Virtual geomagnetic poles do not enter the southern hemisphere.

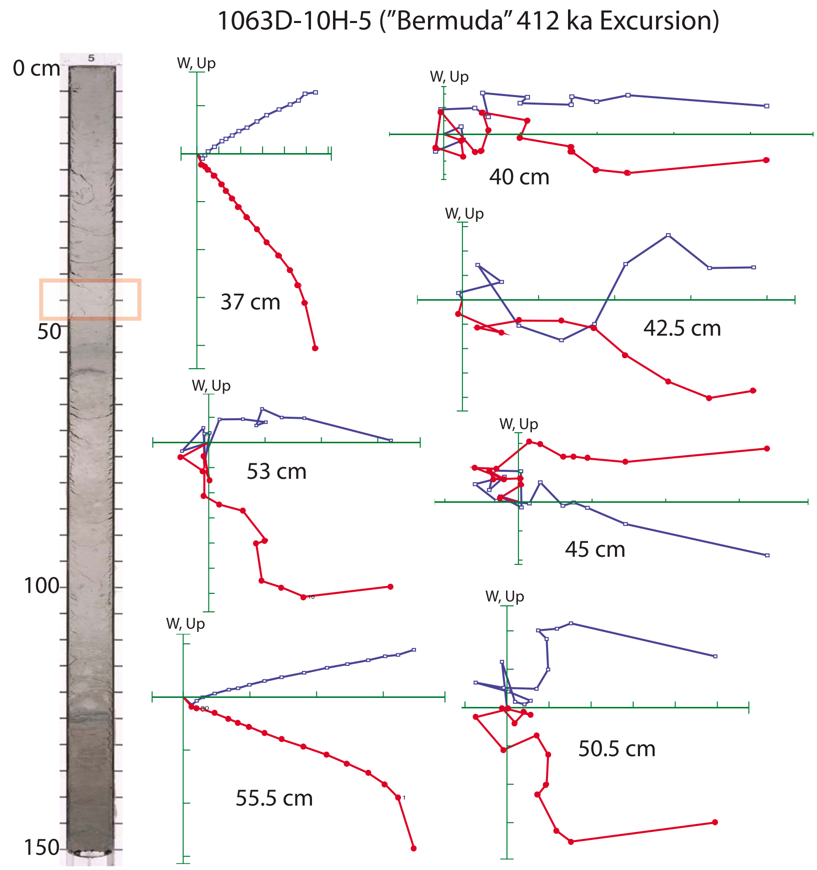

Figure 16. Orthogonal projections of AF demagnetization data for discrete (8 cm^3) samples that record the "Bermuda" (412 ka) excursion. The cm-level in the section is shown for each sample. Red (blue) symbols represent projections onto the vertical (horizontal) planes. The range of peak field demagnetization for each plot is 10–80 mT. Note that declinations in the orthogonal projections are not rotated as for the u-channel data in Figure 15. The shaded box indicates the interval with shallow component inclinations.

intervals, discrete sample inclinations are shallower than expected but remain positive with minimum values of 20°.

7. Conclusions

[24] According to the Site 1063 age model presented here, the ages of three excursions (Laschamp, Blake, Iceland Basin) are consistent with consensus ages for these excursions [e.g., *Lund et al.*, 2006; *Laj and Channell*, 2007] (Table 1). The age of the Pringle Falls excursion at Site 1063 (~238 ka) is older than a recent estimate of 211 ± 13 ka based on ^{40}Ar/^{39}Ar dating at Pringle Falls and in the Albuquerque Volcanics [*Singer et al.*, 2008a], and older than earlier estimates of ~220 ka [*Herrero-Bervera et al.*, 1994; *Liddicoat et al.*, 1998; *McWilliams*, 2001]. The Site 1063 age model is compatible with that of *Grützner et al.* [2002] in this interval (Figure 6), and the excursion corresponds to a prominent paleointensity minimum in the PISO paleointensity stack (Figure 5).

[25] VGPs reach high southerly latitudes for the Laschamp, Blake, Iceland Basin and Pringle Falls excursions at Site 1063, implying that these excursions constitute paired reversals of the main dipole field. These four excursions are labeled "Category 1" (Table 1) implying reversal of the main geomagnetic dipole. The brief (<2 kyr) millennial-scale duration of excursions at Site 1063 (Table 1) is compatible with a hypothesized mechanistic difference between excursions and long-lived reversals [*Gubbins*, 1999], which can explain why reversal transitions can have several times the duration of the paired reversals that constitute Category 1 excursions. These brief duration estimates at Site 1063 (Table 1) are highly dependent on the resolution of the age model, and on the definition of the boundaries of the "excursion." The ~7 kyr estimate for duration of the Iceland Basin excursion at Site 1063 based on

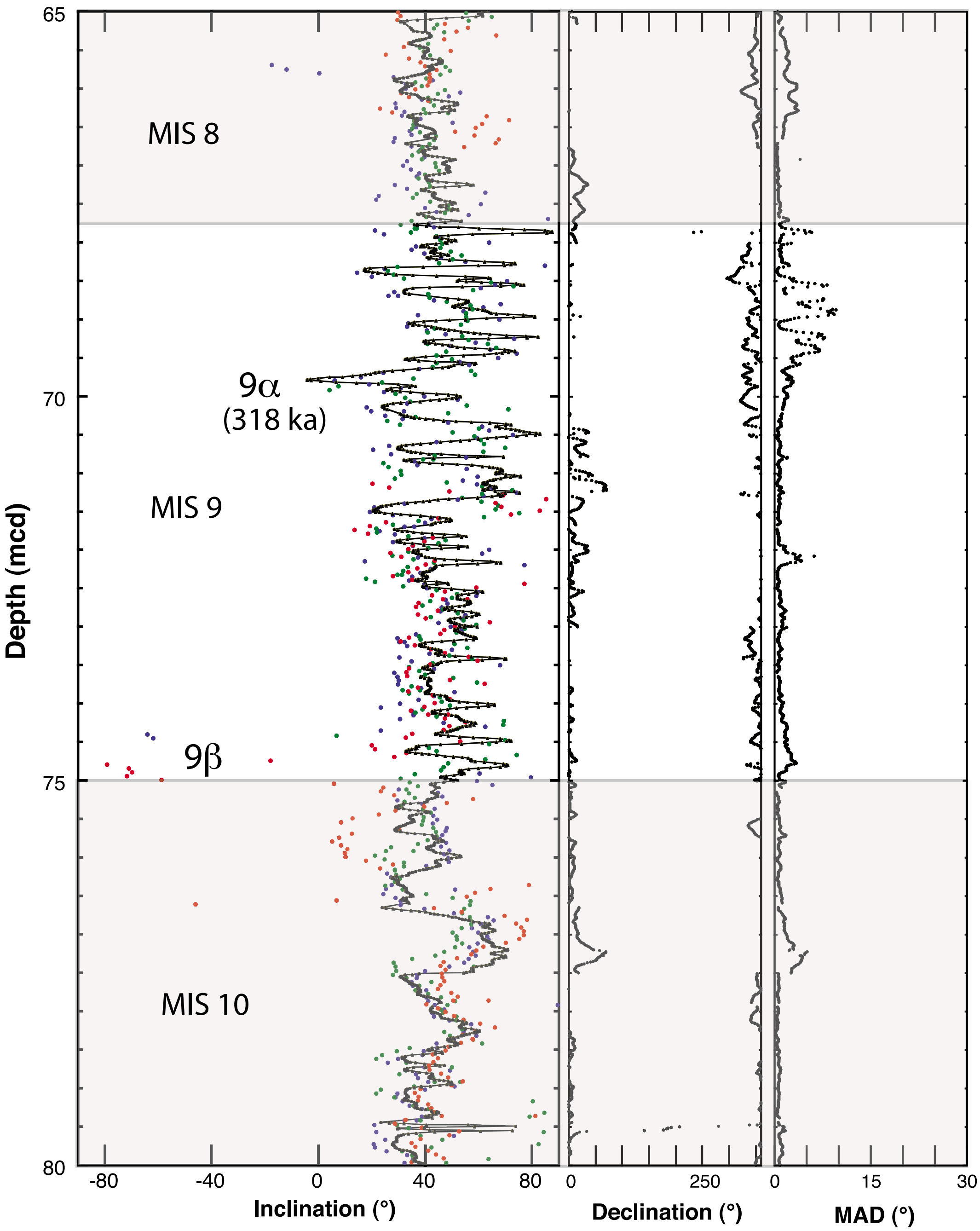

Figure 17. Black indicates Site 1063 u-channel component declination, inclination and maximum angular deviation (MAD) values for the 65–80 mcd interval computed in the 20–80 mT demagnetization interval. In the inclination plot, red indicates Hole 1063A shipboard data after demagnetization at a peak field of 20 mT, blue indicates Hole 1063C shipboard data after demagnetization at a peak field of 20 mT, and green indicates Hole 1063D shipboard data after demagnetization at a peak field of 20 mT. 9α and 9β denote the excursion labels of *Lund et al.* [2001b]. Glacial marine isotopic stages (MIS 8 and MIS 10) are shaded.

excess ^{230}Th [*Knudsen et al.*, 2007] is inconsistent with the estimate given here, not because the two sedimentation rate estimates across the excursion are different, but because *Knudsen et al.* [2007] define the excursional stratigraphic thickness based on the first and last VGP latitude <45° in a wide excursional interval, an excursional thickness four times the excursional thickness for VGP latitudes <0°.

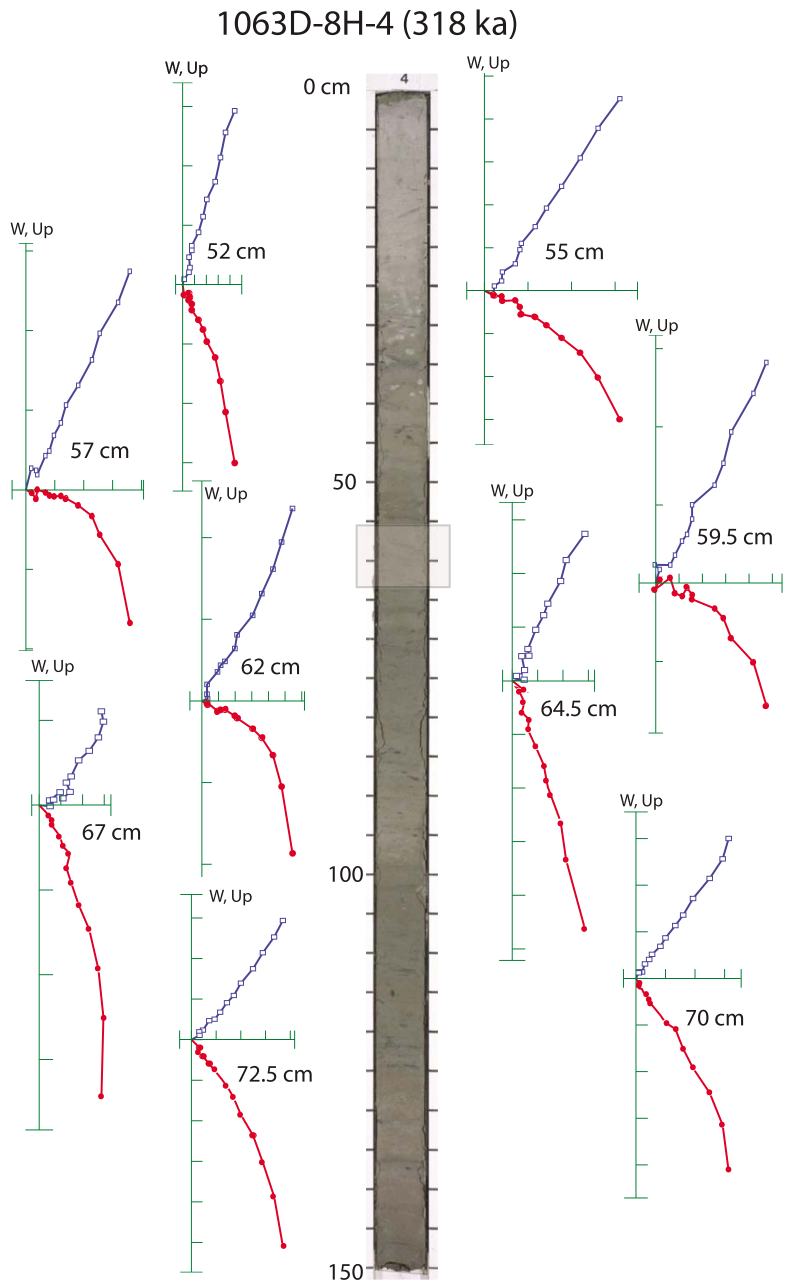

Figure 18. Orthogonal projections of AF demagnetization data for discrete (8 cm^3) samples that record the 318 ka (9α of *Lund et al.* [2001b]) excursion. The cm-level in the section is shown for each sample. Red (blue) symbols represent projection on the vertical (horizontal) planes, respectively. The range of peak field demagnetization for each plot is 10–80 mT. Note that declinations in orthogonal projections are not rotated as for the u-channel data in Figure 17. Shaded box indicates interval of shallow component inclinations.

[26] If geomagnetic excursions comprise paired polarity reversals of the Earth's main dipole, they would be expected to be manifested globally. For this reason, they are an important element in high-resolution stratigraphy. *Laj et al.* [2006] made the case that VGP paths are similar for the Laschamp excursion at dispersed sites, and different but uniform for the Iceland Basin excursion at similarly dispersed sites, implying a dipolar component in the excursional field. In their compilation of VGP paths for the Laschamp and Iceland Basin excursions, *Laj et al.* [2006] observed return and outward VGP paths through Africa for the Laschamp and Iceland Basin excursions, respectively, which is broadly consistent with the VGP paths observed

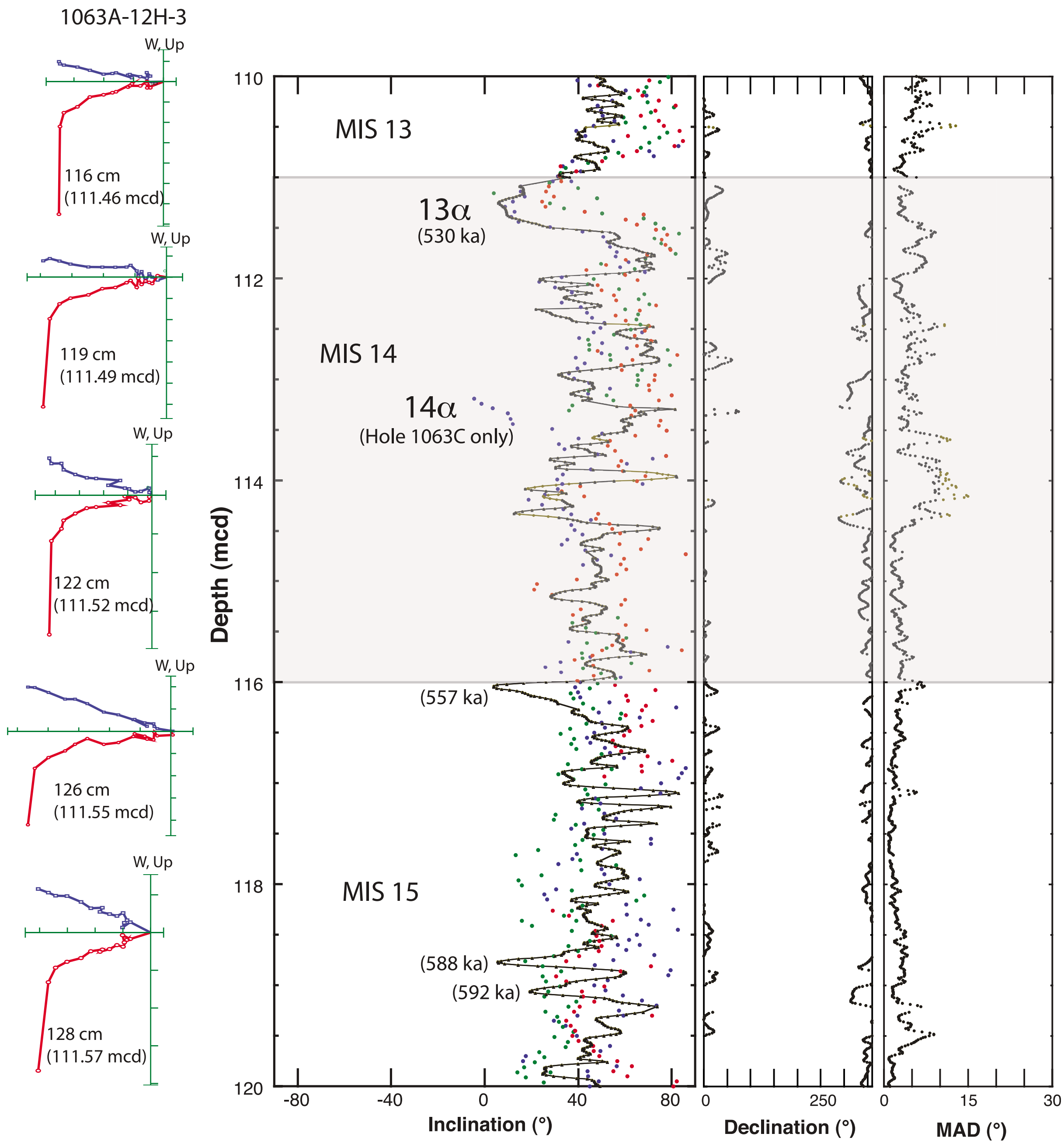

Figure 19. (right) Black indicates Site 1063 u-channel component declination, inclination and maximum angular deviation (MAD) values for the 110–120 mcd interval computed in the 20–80 mT demagnetization interval. In the inclination plot, red indicates Hole 1063A shipboard data after demagnetization at a peak field of 20 mT, blue indicates Hole 1063C shipboard data after demagnetization at a peak field of 20 mT, and green indicates Hole 1063D shipboard data after demagnetization at a peak field of 20 mT. 13α and 14α denote the excursion labels of *Lund et al.* [2001b]. Glacial marine isotopic stage (MIS 14) is shaded. (left) Orthogonal projections of AF demagnetization data for discrete (8 cm^3) samples that record the 530 ka (13α) excursion. The cm-level in the section is shown for each sample. The minimum component inclination (7°) is for sample 126 cm (111.55 mcd). Red (blue) symbols represent projections onto the vertical (horizontal) planes. The range of peak field demagnetization for each plot is 10–80 mT. Note that the declinations in the orthogonal projections are not rotated as for the u-channel data.

here (Figures 7 and 11) although the Site 1063 VGP paths are not completely defined by available data.

[27] There are several intervals with shallow component inclinations older than the Pringle Falls excursion in the Site 1063 u-channel record, and one interval (in Hole 1063C) with shallow negative inclinations at 412 ka (~90 mcd) where VGPs reach low latitudes but do not enter the southern hemisphere (Figure 15). Discrete sample data from Hole 1063D also indicate that this interval at ~412 ka (MIS 11) is characterized by shallow negative inclinations (Figure 16), and the term "Bermuda" excursion is applied. Other intervals of shallow component inclination are observed at ~318 ka (MIS 9) and in the 500–600 ka interval (MIS 14–15) at Site 1063 (Figures 17 and 19). Discrete samples from these intervals indicate shallow component inclinations (down to 7° in the case of the ~318 ka interval), but inclinations do not become negative. The 500–600 ka interval incorporates not only the Big Lost excursion [*Champion et al.*, 1988] at ~565 ka, but also site mean magnetization directions from lava flows in the West Eifel volcanics that yield midlatitude northern-hemisphere VGPs [*Böhnel et al.*, 1987; *Schnepp and Hradetzky*, 1994; *Singer et al.*, 2008b]. The key question is whether these intervals with low component inclinations denote high amplitude secular variation or inadequately recorded magnetic excursions. We propose that excursions characterized by high VGP latitudes in the opposite hemisphere should be termed Category 1 excursions, and those manifest by low latitude VGPs should be termed Category 2 excursions. In the future, improved records may "elevate" Category 2 excursions to Category 1. We do not view this subdivision of Category 1 and Category 2 excursions as necessarily a geomagnetic distinction, but possibly a distinction based on recording fidelity.

[28] It has been known for some time that magnetic excursions and long-lived reversals correspond to paleointensity minima [e.g., *Valet and Meynadier*, 1993]. The five excursions at Site 1063, where negative inclinations are recorded, correspond to paleointensity minima (green stars in Figures 4 and 5). Intervals characterized by shallow positive inclinations, at ~318 ka and ~412 ka, correspond to less extreme paleointensity minima at Site 1063 and in the PISO stack, and the 500–600 ka interval corresponds to an extended period with low RPI at Site 1063 that is anomalous relative to the PISO stack (Figure 5). Other paleointensity minima in the Brunhes Chron (and further back in time) may be associated with directional excursions, but the documentation of excursions remains elusive because of their brief (<2 kyr) duration that often precludes their recording at sedimentation rates less than ~15 cm/kyr, due to bioturbation and progressive lock-in of magnetization in deep-sea sediments.

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