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11. Paleomagnetic Records of Stage 3 Excursions, Leg 172[1]

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ABSTRACT

Shipboard long-core paleomagnetic measurements made during Ocean Drilling Program Leg 172 identified a reproducible pattern of directional secular variation between ~15,000 and 45,000 k.y. that could be correlated between Sites 1061, 1062, and 1063, which span a distance of more than 1200 km. Two intervals of excursional paleomagnetic directions were identified at all three sites and were labeled as excursions 3α and 3β. New analysis of excursions 3α and 3β, based on reassessment of the shipboard measurements, new U-channel paleomagnetic records of the excursions, and independently published discrete sample paleomagnetic records of the same intervals all indicate that excursion 3α is not real; its directional variability is less than originally estimated and not excursional. Excursion 3β is real and easily identified in both U-channel and discrete sample measurements. Excursion 3β is the Laschamp Excursion noted in previous published studies. The best U-channel record of excursion 3β from Hole 1063C is almost identical to the best discrete sample paleomagnetic records. The U-channel records from Holes 1061B and 1061C are similar to one another but somewhat different from the other records (more smoothed). We attribute that difference to systematic biases in the U-channel measurement process when large-amplitude, fast directional changes occur.

INTRODUCTION

During Ocean Drilling Program (ODP) Leg 172, almost 6 km of Pliocene/Pleistocene deep-sea sediments was recovered from three sedi-

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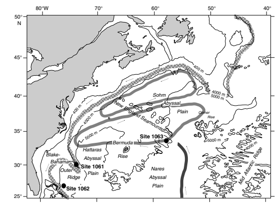
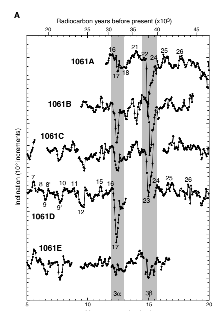
ment drifts (Keigwin and Jones, 1989) of the western North Atlantic Ocean: the Blake Outer Ridge (Sites 1054–1061), the Bahama Outer Ridge (Site 1062), and the Bermuda Rise (Site 1063) (Keigwin, Rio, Acton, et al., 1998). These sediment drifts (see Fig. F1) are regions of anomalously high sediment accumulation rates (typically 10–40 cm/k.y.), and they contain perhaps the highest resolution record of geomagnetic field variability ever recovered from deep-sea sediments. Sediments in the uppermost 150–220 m of each site were collected using the advanced piston corer (APC), which is capable of recovering almost pristine cores of soft sediment. Aboard ship, we measured the archive halves of all sediment cores using a new long-core cryogenic magnetometer (Model 760 from 2G Enterprises) with an in-line alternating magnetic–field (AF) demagnetizer, which was installed after ODP Leg 169. From the long-core measurements, we were able to estimate the pattern of geomagnetic field secular variation (both directions and intensity) for the Brunhes Chron and identify 14 "plausible" Brunhes-aged magnetic field excursions (Keigwin, Rio, Acton, et al., 1998; Lund et al., 1998).

F1. Map of the western North Atlantic Ocean showing site locations, p. 8.



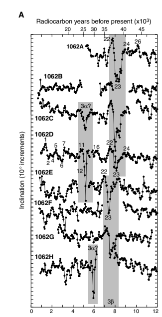
F2. Long-core inclination and declination measurements, Site 1061, p. 9.



This paper considers in more detail excursions labeled 3α and 3β by Lund et al. (1998; Chap. 10, this volume). We reconsider the shipboard long-core paleomagnetic results that led us to suggest these excursions existed, we present new U-channel paleomagnetic records for three replicate sediment sections containing excursions 3α and 3β (= Laschamp Excursion), and we compare these results with independent discrete sample paleomagnetic results from the same time interval (Schwartz et al., 1997; Lund et al., in press). These results confirm the existence of excursion 3β but not 3α. They also show that long-core and U-channel measurements in excursion intervals, characterized by fast changes in field direction and/or intensity, may not be able to routinely recover the detailed pattern of directional field variability.

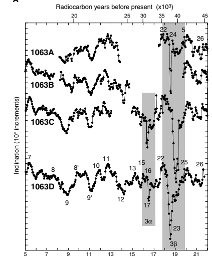
INITIAL IDENTIFICATION OF EXCURSIONS 3α AND 3β

F3. Long-core inclination and declination measurements, Site 1062, p. 11.



Records of magnetic field secular variation within ODP Leg 172 cores were estimated aboard ship by measuring the sediment natural remanent magnetization (NRM) of all cores (archive halves) at 5-cm spacing after 20-mT AF demagnetization. The 20-mT demagnetization removed a ubiquitous low-coercivity drill-stem magnetic overprint that has been noted previously on many ODP legs (e.g., Nagy and Valet, 1993; Weeks et al., 1993). Further AF demagnetization of selected core segments usually showed good characteristic remanences that decayed toward the origin (Keigwin, Rio, Acton, et al., 1998). Stepwise AF demagnetization of discrete samples from selected horizons also displayed the same behavior (Keigwin, Rio, Acton, et al., 1998).

F4. Long-core inclination and declination measurements, Site 1063, p. 13.



The patterns of directional variability observed after demagnetization could commonly be correlated between holes at individual sites for Sites 1060–1063. For example, inclination and declination variability at Site 1061 (Blake Outer Ridge, five holes) from ~15,000 to 45,000 k.y. is shown in Figure F2; similar variability at Site 1062 (Bahama Outer Ridge, eight holes) and Site 1063 (Bermuda Rise, four holes) is shown in Figures F3 and F4. The chronologies for these three records was developed using radiocarbon dates from Keigwin and Jones (1994), which were correlated to these sites using magnetic susceptibility and calcium carbonate variations (Lund et al., in press; Keigwin, Rio, Acton, et al., 1998; see also Lund et al., Chap. 10, this volume).

It is clear for all three sites that selected inclination and declination features (numbered in Figs. F2, F3, and F4) can be traced among the records from independent holes separated by distances of <1 km. The most diagnostic features are narrow intervals of distinctive low/high inclination or easterly/westerly declination. In between these most easily correlated features, it is common to see more subtle patterns of variability that are also consistent between holes. The directional secular variation in selected time intervals can also be correlated between sites up to 1600 km apart. For example, compare the inclination and declination variability from ~15,000 to 45,000 k.y. as recorded at Site 1063 (Bermuda Rise) (Fig. F4) vs. Site 1061 (Blake Outer Ridge) (Fig. F2).

The secular variation records in Figures F2, F3, and F4 consistently contain two intervals (highlighted in Figs. F2, F3, and F4) wherein inclination and declination variability is significantly higher in amplitude and inclinations are negative. These directions (after correction for overall core orientation) yield virtual geomagnetic poles (VGPs) that are more than 45° away from the North Geographic Pole; such VGPs are termed excursional (Verosub and Banerjee, 1977) and may reflect times of unusual geomagnetic field behavior. We identified these two intervals as "plausible" excursions on the basis of three criteria: (1) presence of true excursional directions, (2) occurrence in at least four different holes at two or more sites, and (3) location of excursional directions within a reproducible and correlatable pattern of more typical secular variation. The younger excursion was labeled "3α" and the older was labeled "3β."

More careful assessment of the paleomagnetic results in Figures F2, F3, and F4 raises some concern about the reality of excursion 3α. Excursion 3α is present and associated with inclination low "17" in three of five holes at Site 1061 and in both holes at Site 1063. Excursion 3α is missing from the other holes either because of some type of magnetic "smearing" or stratigraphic gaps. At Site 1062, what we originally interpreted as excursion 3α is associated with inclination low "12′" in two of five holes and is associated with inclination low "17′" in only one of eight holes. Thus, evidence that excursion 3α occurs within a reproducible pattern of secular variation is less certain than noted previously (Keigwin, Rio, Acton, et al., 1998; Lund et al., 1998).

U-CHANNEL PALEOMAGNETIC MEASUREMENTS OF EXCURSIONS 3α AND 3β

We have now recovered replicate U-channel paleomagnetic records of excursions 3α and 3β from three holes: 1061B, 1061C, and 1063C. U-channel measurements (without deconvolution) were made at the University of California-Davis using the specialized U-channel cryogenic magnetometer in Professor Ken Verosub's laboratory. The U-channels were AF demagnetized sequentially in 10-mT steps up to 60 or 80 mT. The AF-demagnetization diagrams of individual horizons, both inside and outside of excursional intervals, routinely showed a linear decay toward the origin above 20 mT (Keigwin, Rio, Acton, et al., 1998). Subsequently, the U-channels were remagnetized with an anhysteretic remanent magnetization (ARM) and stepwise AF demagnetized up to 60 mT, then remagnetized with a saturation isothermal remanent magnetization (SIRM) acquired at 1 T; in some cases back-IRMs were sequentially applied at 0.1 and 0.3 T and measured. The U-channel rock-magnetic results are identical to those of Schwartz et al. (1997) from studies of piston cores collected during the site survey associated with Leg 172.

The shipboard long-core (half round) measurements and U-channel measurements for all three holes (after 20-mT AF demagnetization) are compared in Figures **F5, F6,** and **F7.** In all three cases, the anomalously low inclination associated with excursion 3α disappears in the U-channel measurements; the resulting U-channel directional variability does not contain excursional VGPs. The anomalous directional variability of excursion 3β is still present in all three holes, complete with excursional VGPs, but the detailed directional patterns display some significant differences between the shipboard and U-channel measurements and between Sites 1061 and 1063.

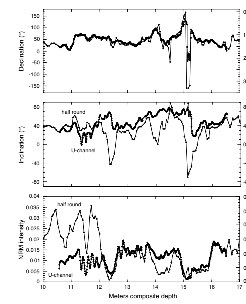
The inclination and declination records for excursions 3α and 3β in Holes 1061B and 1061C are overlain in Figure **F8.** Allowing for ~20 cm of offset between the two holes in the modified composite depth (mcd), it is clear that a reproducible pattern of secular variation is still present, although exact details in amplitude are not always the same. Both data sets contain similar records of excursion 3β with the same pattern of inclination and declination variability as well as a consistent phase relationship between them. However, excursion 3β in Hole 1061C is slightly more subdued (smeared) than in Hole 1061B.

These records can be compared with discrete sample paleomagnetic records of the Laschamp Excursion (= excursion 3β) previously recovered from the same area by Lund et al. (in press). Paleomagnetic records from core JPC14 on the Blake Outer Ridge and core CH89-9P from the Bermuda Rise are shown in Figure **F9.** The two discrete sample paleomagnetic records are almost identical in their directional variability even though they are separated by more than 1200 km. They both show a clear directional phase relationship wherein the largest westerly to easterly declination swing occurs during a time of large negative inclinations. In the U-channel records from Site 1061, the westerly to easterly declination swing occurs significantly later within an interval of high positive inclinations. We think that the discrete sample paleomagnetic records are correct and that the apparent difference in phase relationship in the Site 1061 U-channels is an artifact of the integrative, continuous measurement process and sediment smearing. The differences in smearing may be related to overall sediment accumulation rates on the Blake Outer Ridge.

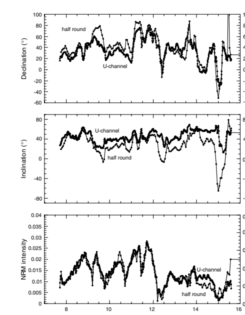
Figure **F10** shows the average sediment accumulation rates across the Blake-Bahama Outer Ridge for the last glacial cycle. Site 1061 has an average rate of 30 cm/k.y., Site 1062 has a rate of 22 cm/k.y., and core JPC14 has a rate of 37 cm/k.y. The lower accumulation rate at Site 1061 may contribute to producing a more smeared record of excursion 3β relative to core JPC14 (or Site 1062). Corroboration for this can be noted by the results of Lund (1993; Lund et al., in press) where they note that the Laschamp excursion record in core CH88-10P from the Blake Outer Ridge (22 cm/k.y. average accumulation rate) (see Fig. **F10**) produced a strongly smeared record of the Laschamp Excursion with no excursional VGPs.

A comparison of the excursion 3β paleomagnetic record from Hole 1063C with these other records is also instructive. First, there is a more significant difference between the shipboard and U-channel measurements of the same core (Fig. **F7**). However, the U-channel record from

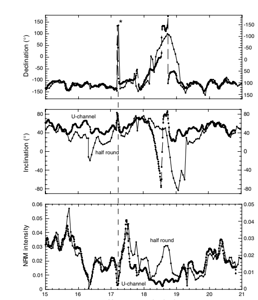
F5. Comparison of half-round and U-channel long-core paleomagnetic measurements, Hole 1061B, p. 15.



F6. Comparison of half-round and U-channel long-core paleomagnetic measurements, Hole 1061C, p. 16.



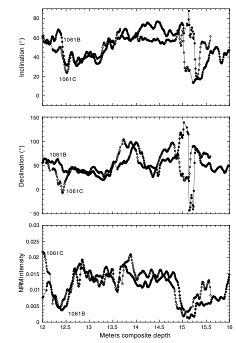
F7. Comparison of half-round and U-channel long-core paleomagnetic measurements, Hole 1063C, p. 17.



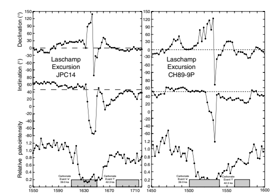
Hole 1063C is much more consistent with the discrete sample records and U-channel records from Site 1061 than with its own shipboard measurements. The problem may be related to anomalous, and unexplainable, higher NRM intensity at ~18.6 mcd in the shipboard measurements that is not reproduced in the U-channel measurements. The Hole 1063C U-channel record comes closest of all the records to replicating the discrete sample paleomagnetic records. Hole 1063C displays almost complete reversal in declination with inclinations reaching almost –80°; this is nearly identical to the record from core CH89-9P (Fig. F9), located within a few kilometers of Hole 1063C. In Hole 1063C, the westerly to easterly declination change is associated with high positive inclinations that occur just before the large negative inclination interval, but the differences in phase with core CH89-9P are much more subtle than those noted at Site 1061. All in all, it appears that Hole 1063C faithfully records excursion 3β in a manner consistent with the discrete sample records described by Lund et al. (in press).

One final complication, which we have previously noted in both long-core and U-channel measurements, is the presence of narrow intervals with very high positive inclinations (>80°), often with large declination variability, which have excursional VGPs. An example (starred interval) is shown for Hole 1063C in Figure F7. We noticed this first aboard ship during long-core measurements, and, in several instances, could ascribe the effect to narrow intervals with distinctive lithology and anomalously high or low NRM intensity. The same effect is apparent in Figure F7. We presume that the feature in Figure F7 is an artifact of U-channel measurement in an interval of fast NRM intensity change and does not reflect true geomagnetic field variability.

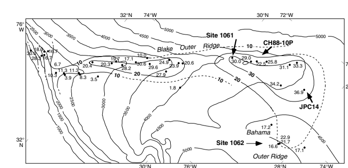
F8. Comparison of excursion 3β as recorded in Holes 1061B and 1061C, p. 18.



F9. Paleomagnetic records of the Laschamp Excursion, p. 19.



F10. Bulk sediment accumulation rates for Stages 1–4, p. 20.



DISCUSSION

The paleomagnetic records from Leg 172 cores described above generally illustrate the ability of the Ocean Drilling Program to acquire state-of-the-art paleomagnetic field records from deep-sea sediments using the APC corer and, with definable limitations, to evaluate the sediment paleomagnetism using the shipboard cryogenic magnetometer, correlate secular variation on at least a site basis, and identify "plausible" magnetic field excursions for further analysis. The U-channel measurements indicate, however, that selected secular variation or excursional features noted in the shipboard long-core measurement processes may be artifacts of the measurement process and require careful analysis and corroboration. Specifically, excursion 3α appears to be a systematic artifact of shipboard measurements. The U-channel records provide a significantly better record of the secular variation around excursion 3α and indicate that the interval does not contain excursional VGPs.

U-channel measurements of excursion 3β verify its existence and provide good corroboration of its overall directional character. The U-channel records from Site 1061, however, still appear to display systematic differences with discrete sample paleomagnetic records from the same region that we interpret to indicate variable sediment smearing and systematic biases associated with the U-channel long-core measurement process. The U-channel record from Site 1063 displays a higher resolution view of excursion 3β that is generally consistent with discrete sample measurements from the same locality.

This study, in conjunction with the shipboard results described in Lund et al. (1998) and Keigwin, Rio, Acton, et al. (1998), represents the first successful attempt to use secular variation records from ODP cores to correlate between sites on a scale of more than 1000 km. It shows that excursion 3β is a real geomagnetic feature that resides within an extended interval of reproducible secular variation.

CONCLUSIONS

Shipboard long-core paleomagnetic measurements made during Leg 172 identified a reproducible pattern of directional secular variation within oxygen isotope Stage 3 that could be correlated between Sites 1061, 1062, and 1063, which span a distance of more than 1200 km. Two intervals of excursional paleomagnetic directions were identified at all three sites within Stage 3 and were labeled as excursions 3α and 3β. New analysis of excursions 3α and 3β, based on the shipboard measurements, new U-channel paleomagnetic records of the excursions, and independently published discrete sample paleomagnetic records of the same intervals all indicate that excursion 3α is not real; its directional variability is less than originally estimated and not excursional. Excursion 3β is real and easily identified in both U-channel and discrete sample measurements. The best U-channel record of excursion 3β from Hole 1063C is almost identical to the best discrete sample paleomagnetic records. The U-channel records from Holes 1061B and 1061C are similar to one another but somewhat different from the other records (more smoothed). We attribute that difference to systematic biases in the U-channel measurement process when large-amplitude, fast directional changes occur.

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Figure F1. Map of the western North Atlantic Ocean showing the locations of Sites 1061, 1062, and 1063 for Ocean Drilling Program Leg 172. Lines indicate the general pattern of deep ocean circulation around these sites.

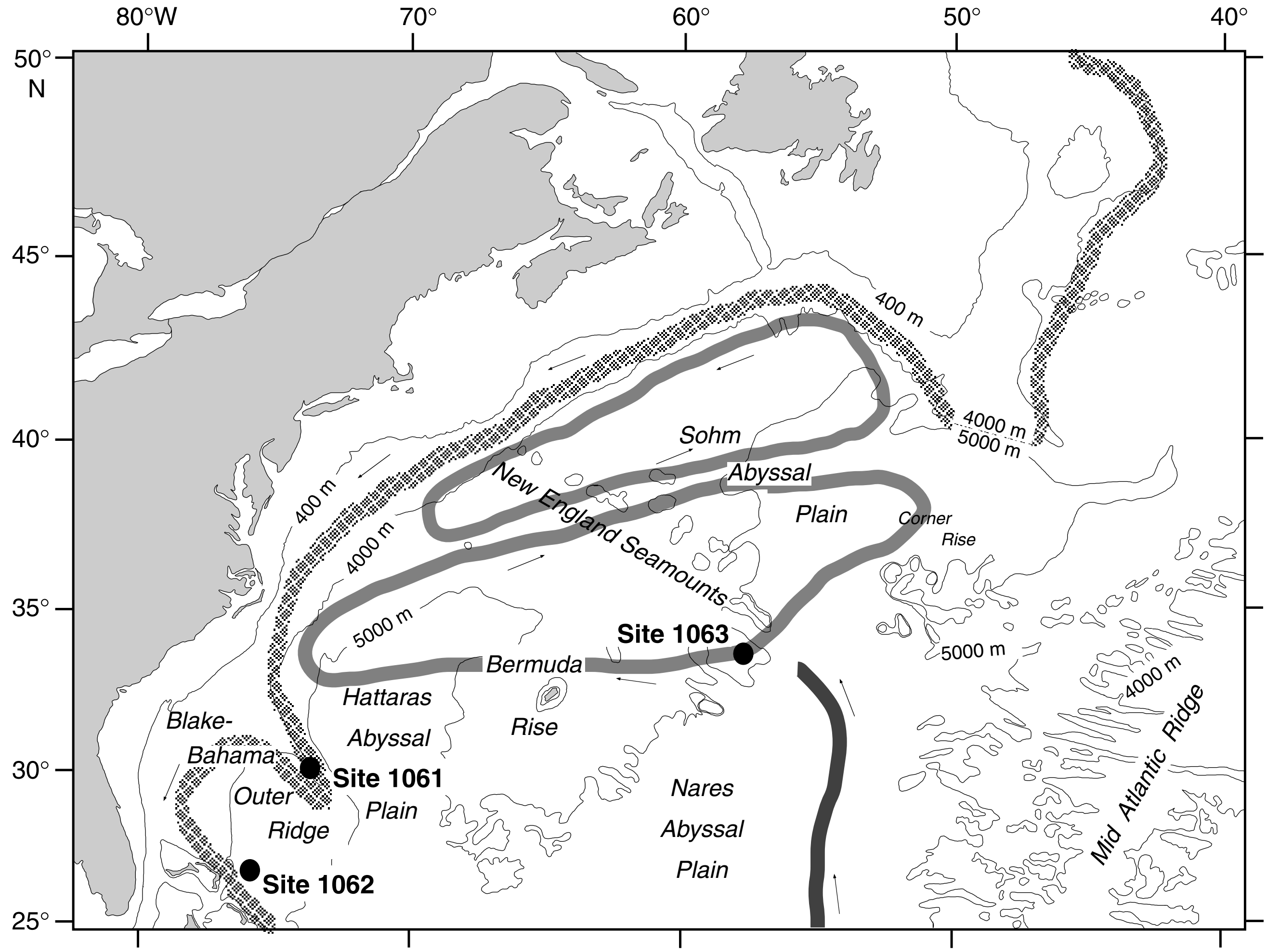

Figure F2. **A.** Long-core inclination for all five holes at Site 1061 (Blake Outer Ridge). Selected inclination and declination features are numbered for comparison with similar features in Figures F3, p. 11, and F4, p. 13. The hatched areas indicate two "plausible" excursion intervals, 3α and 3β, based on shipboard long-core paleomagnetic measurements (Keigwin, Rio, Acton, et al., 1998; Lund et al., 1998). (Continued on next page.)

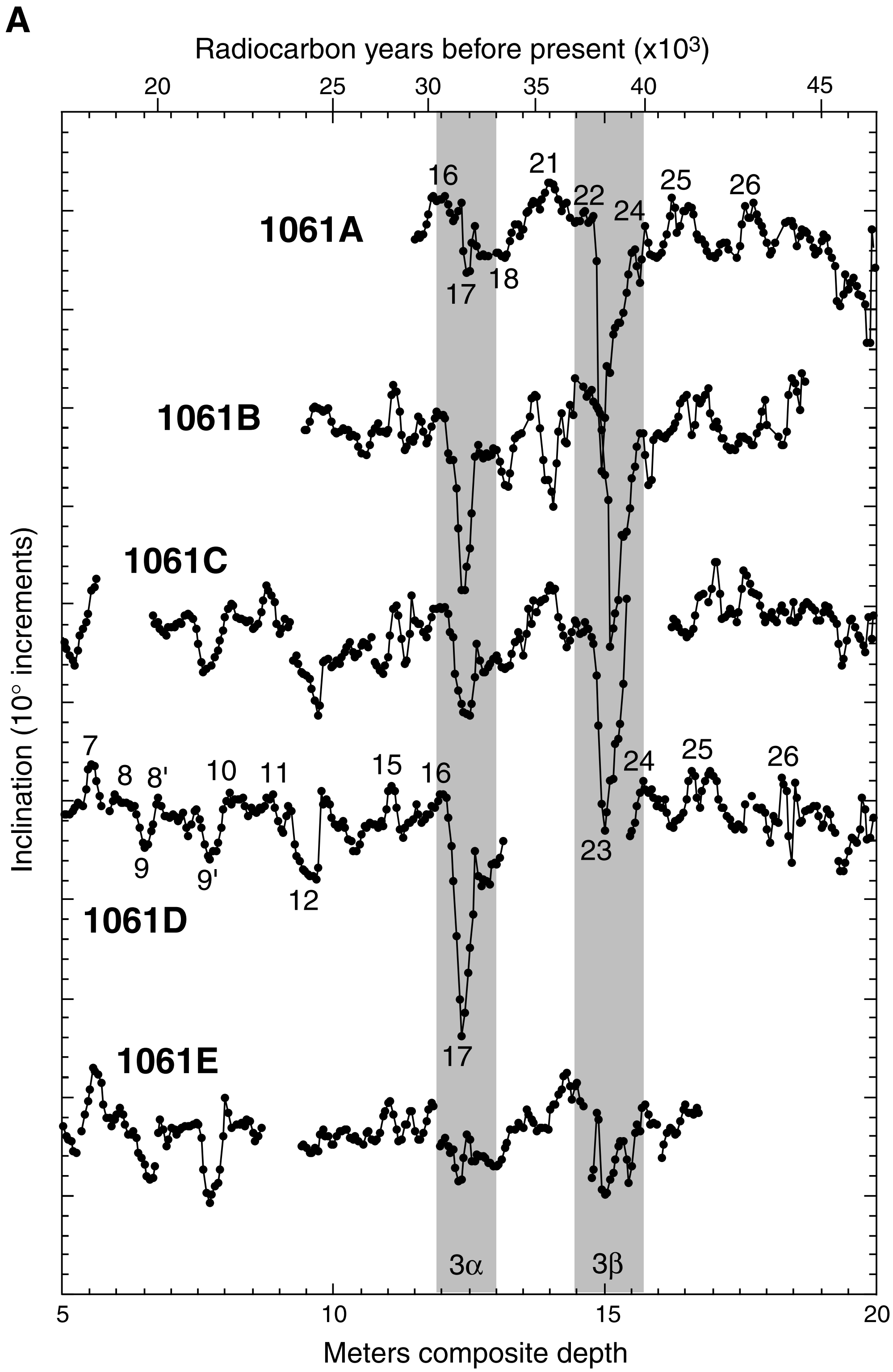

Figure F2 (continued). B. Long-core declination measurements (20-mT AF demagnetization), Site 1061.

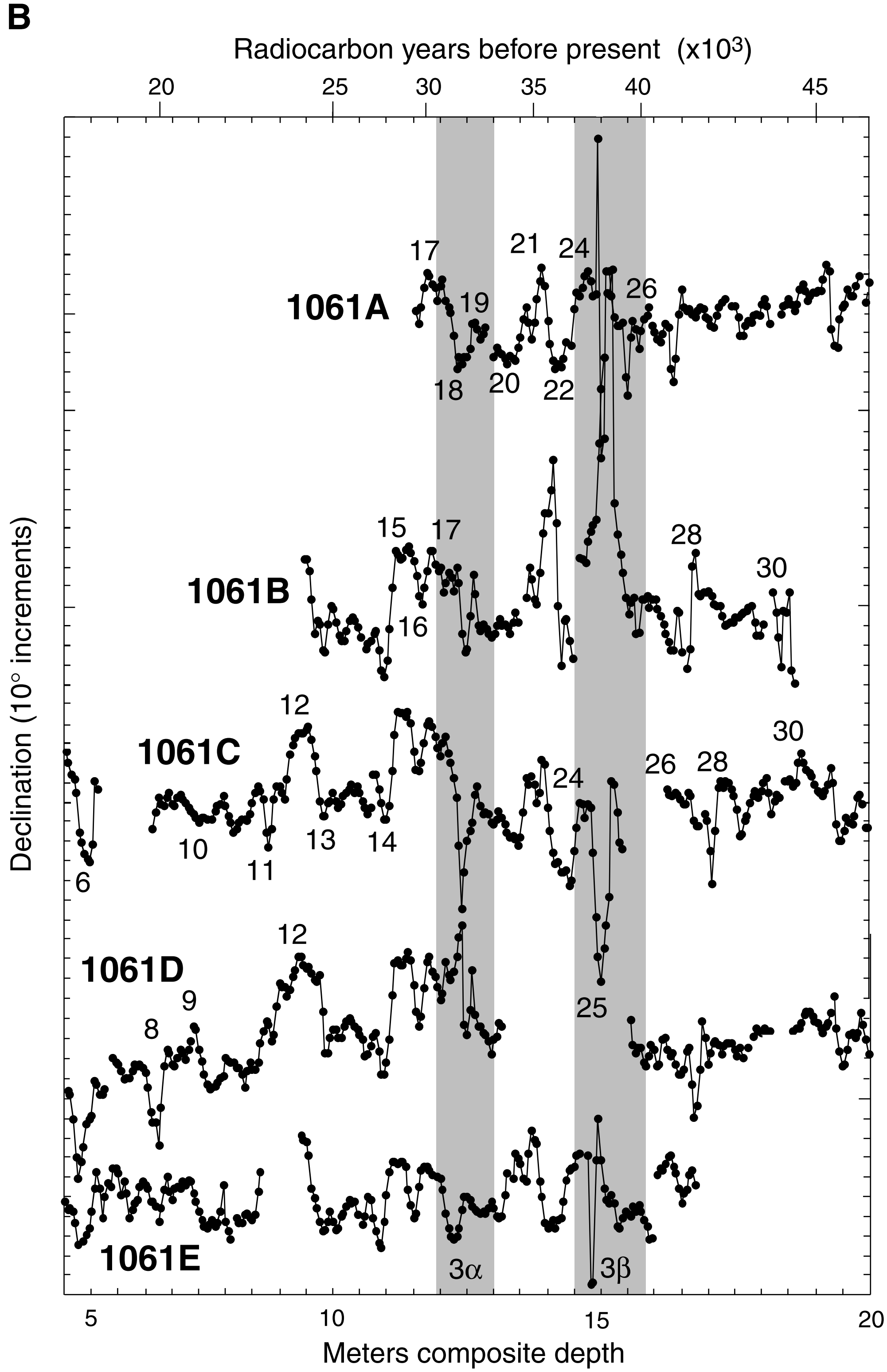

Figure F3. **A.** Long-core inclination for all four holes at Site 1062 (Bahama Outer Ridge). Selected inclination and declination features are numbered for comparison with similar features in Figures F2, p. 9, and F4, p. 13. The hatched areas indicate two "plausible" excursion intervals, 3α and 3β, based on shipboard long-core paleomagnetic measurements (Keigwin, Rio, Acton, et al., 1998; Lund et al., 1998). (Continued on next page.)

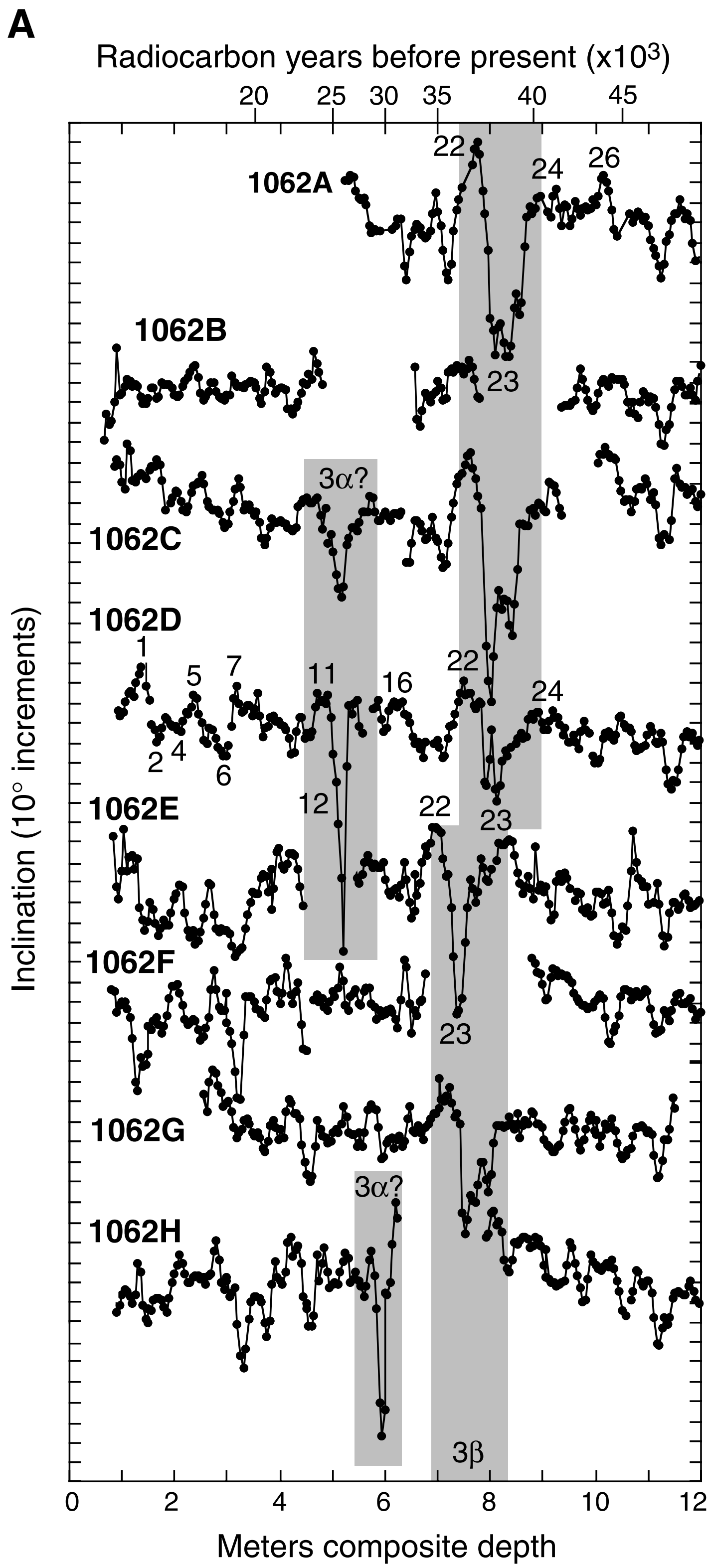

Figure F3 (continued). B. Long-core declination measurements (20-mT AF demagnetization), Site 1062.

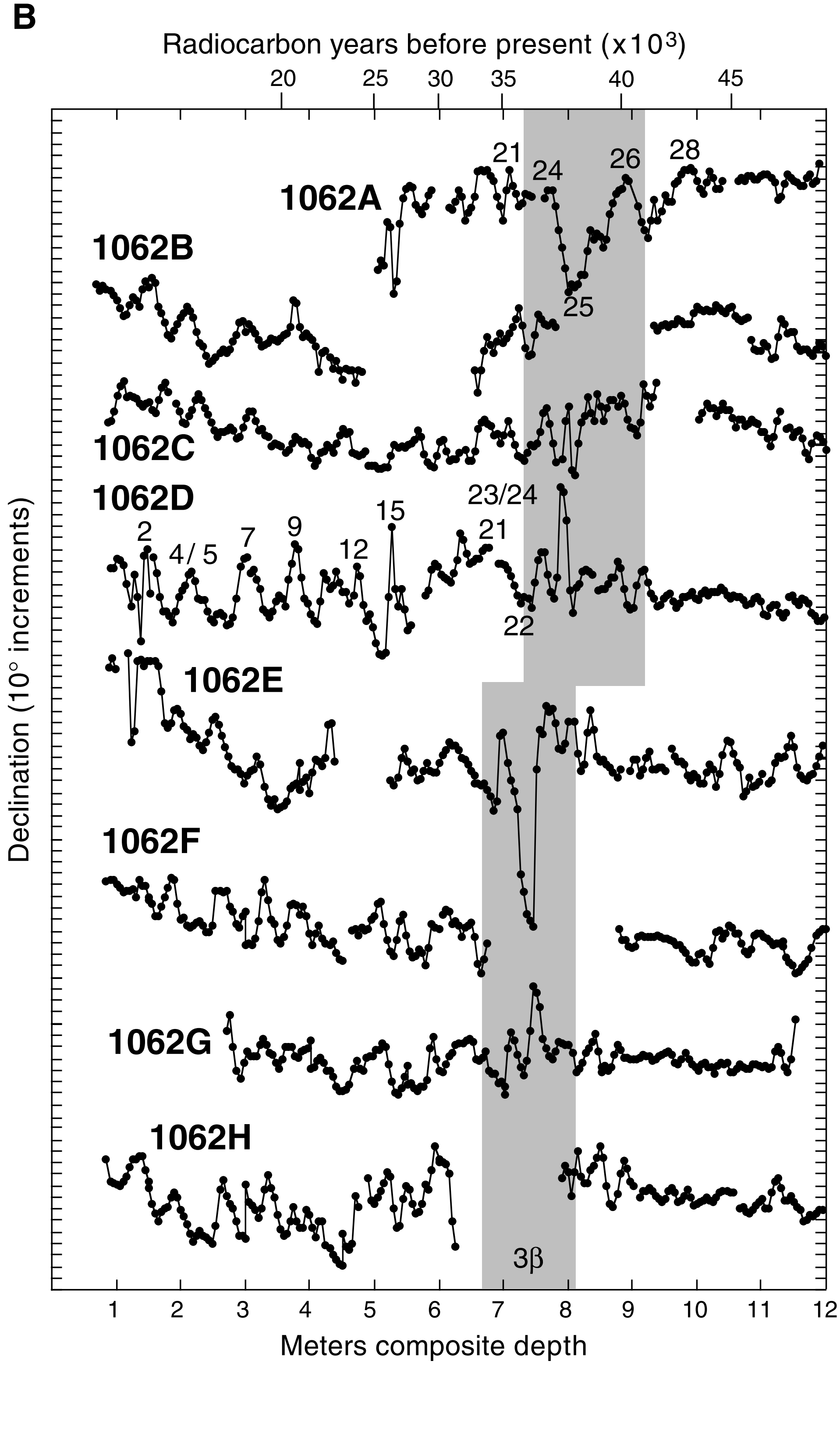

Figure F4. **A.** Long-core inclination for all four holes at Site 1063 (Bermuda Rise). Selected inclination and declination features are numbered for comparison with similar features in Figures F2, p. 9, and F3, p. 11. The hatched areas indicate two "plausible" excursion intervals, 3α and 3β, based on shipboard long-core paleomagnetic measurements (Keigwin, Rio, Acton, et al., 1998; Lund et al., 1998). (Continued on next page.)

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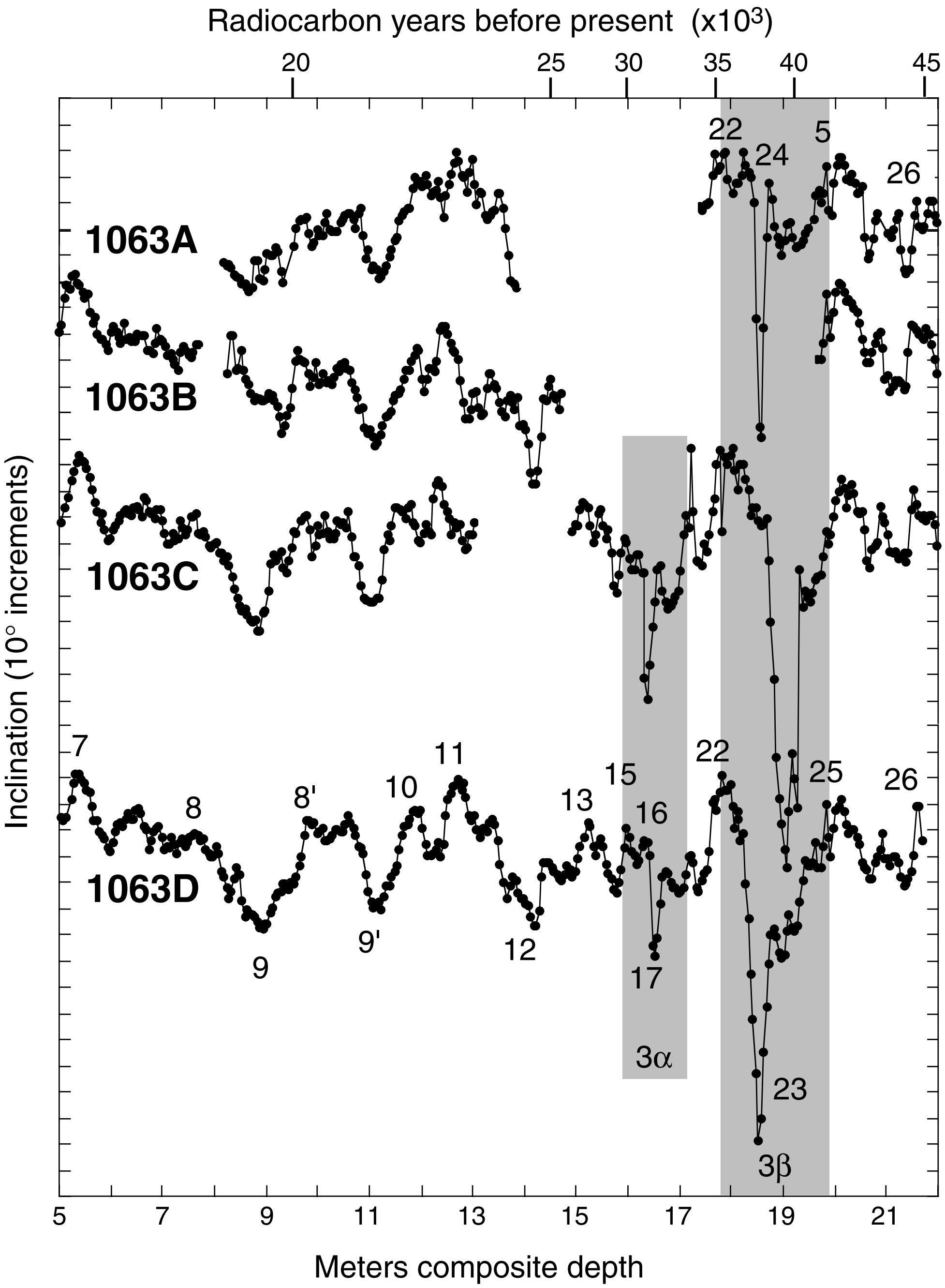

Figure F4 (continued). B. Long-core declination measurements (20-mT AF demagnetization), Site 1063.

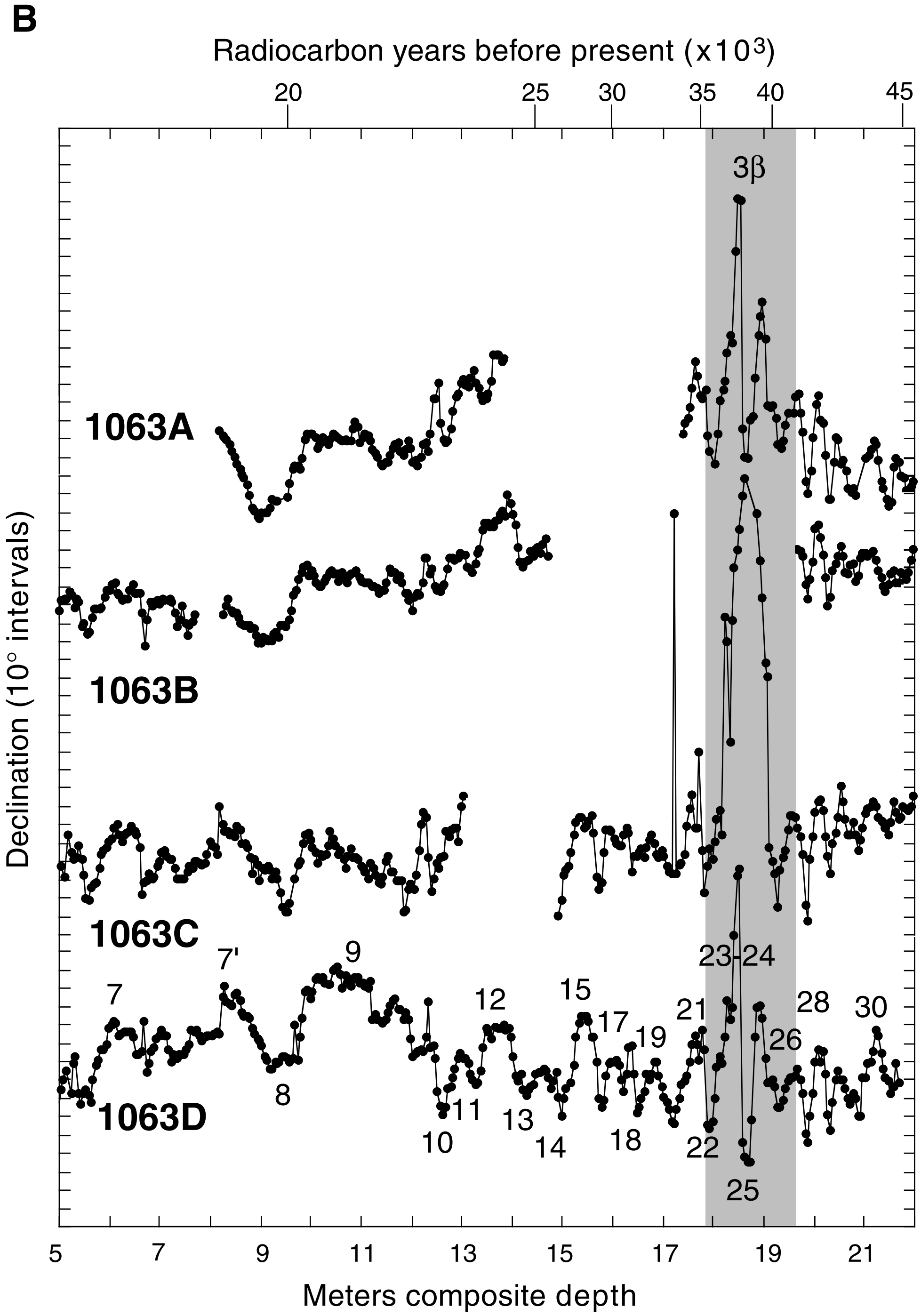

Figure F5. Comparison of shipboard (half round) and U-channel long-core paleomagnetic measurements (after-20 mT AF demagnetization) for an interval containing excursions 3α and 3β in Hole 1061B. See **"U-Channel Paleomagnetic Measurements of Excursions 3α and 3β,"** p. 3, for more detailed discussion.

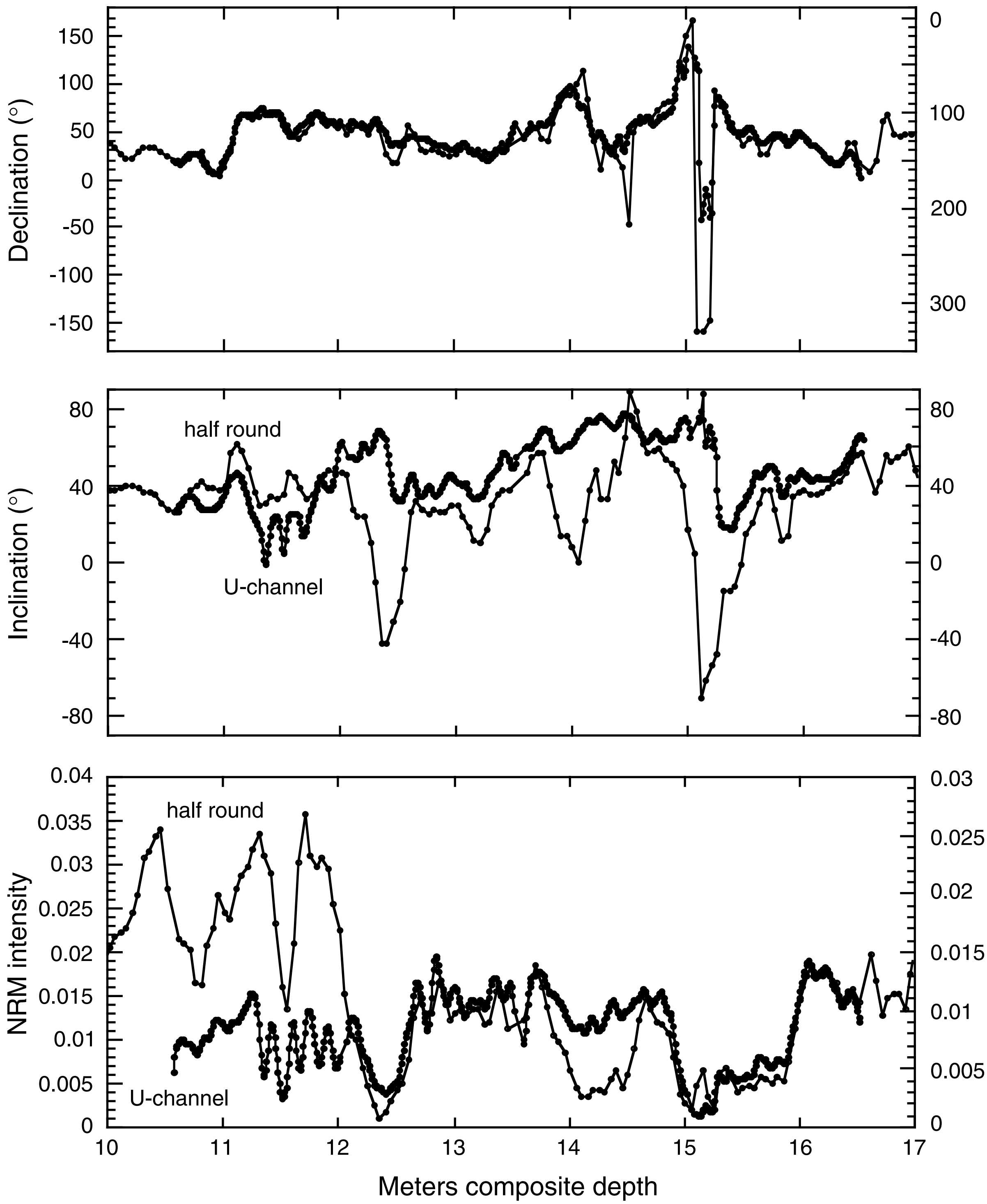

Figure F6. Comparison of shipboard (half round) and U-channel long-core paleomagnetic measurements (after 20-mT AF demagnetization) for an interval containing excursions 3α and 3β in Hole 1061C. See **"U-Channel Paleomagnetic Measurements of Excursions 3α and 3β,"** p. 3, for more detailed discussion.

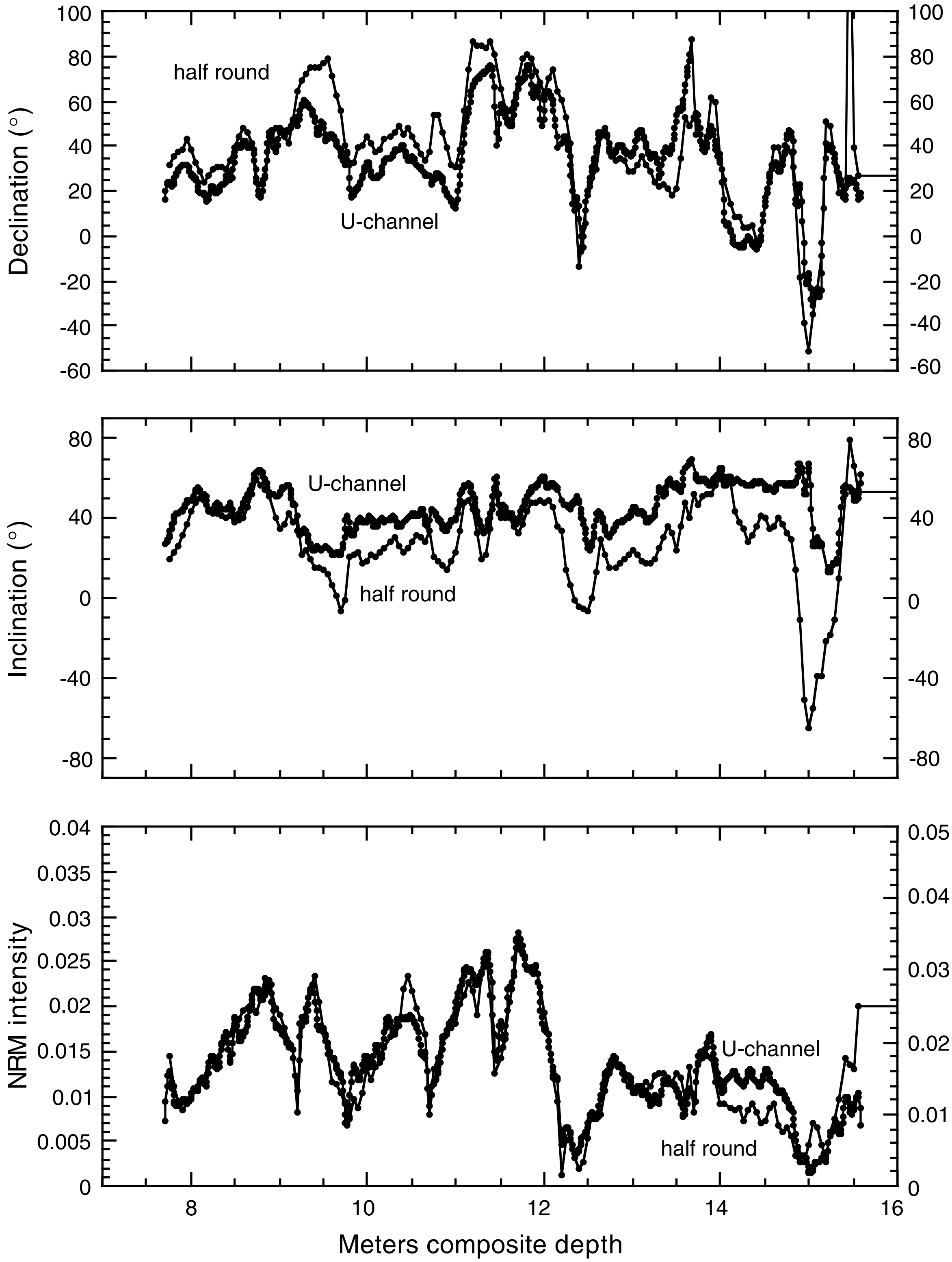

Figure F7. Comparison of shipboard (half round) and U-channel long-core paleomagnetic measurements (after 20 -mT AF demagnetization) for an interval containing excursions 3α and 3β in Hole 1063C. See **"U-Channel Paleomagnetic Measurements of Excursions 3α and 3β,"** p. 3, for more detailed discussion.

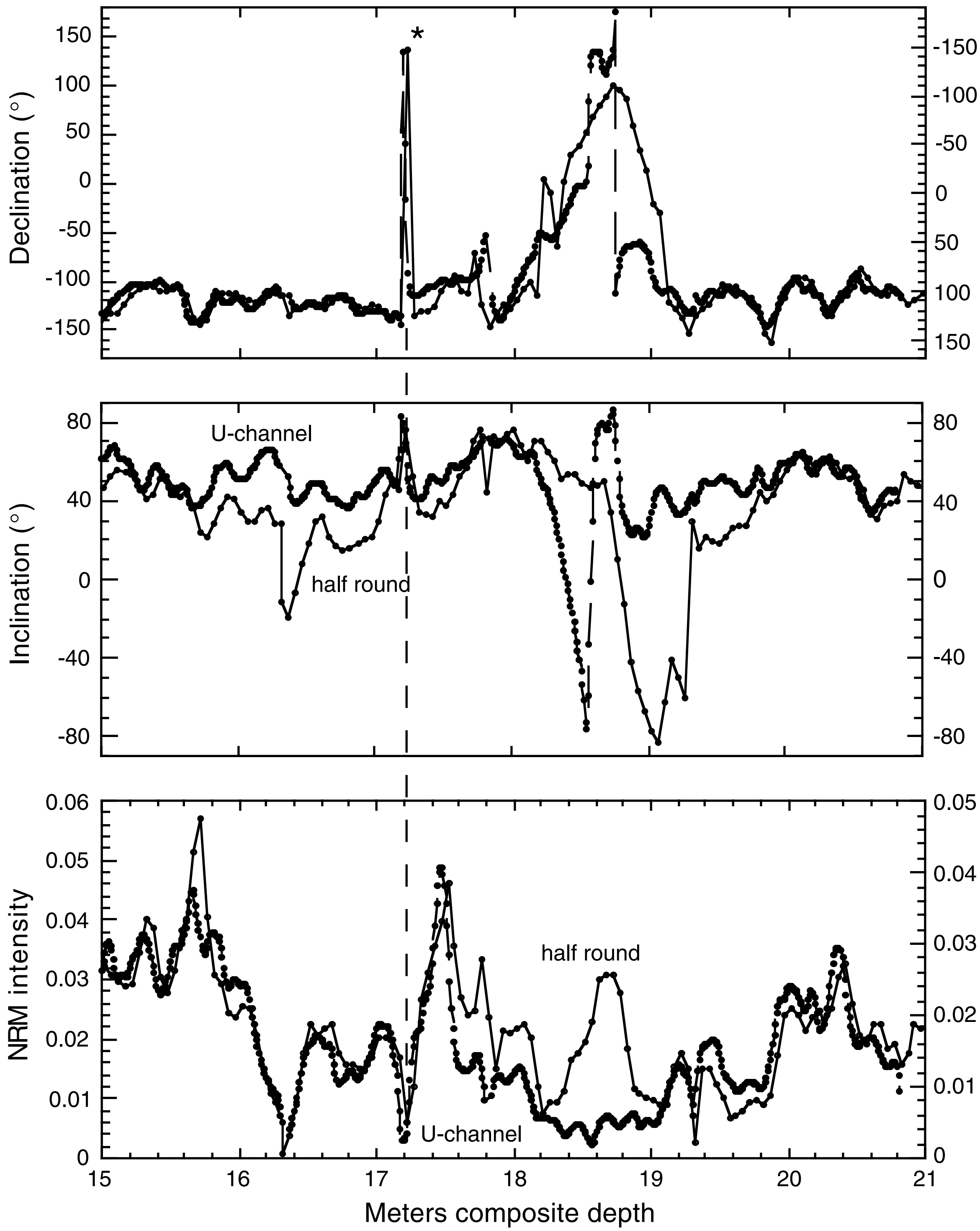

Figure F8. A comparison of excursion 3β as recorded in Holes 1061B and 1061C. The depth scale is provided by magnetic susceptibility correlations between all the holes at Site 1061. There are still ~20 cm offsets between equivalent individual paleomagnetic features at the two holes due to more subtle variations in sediment accumulation at the two holes.

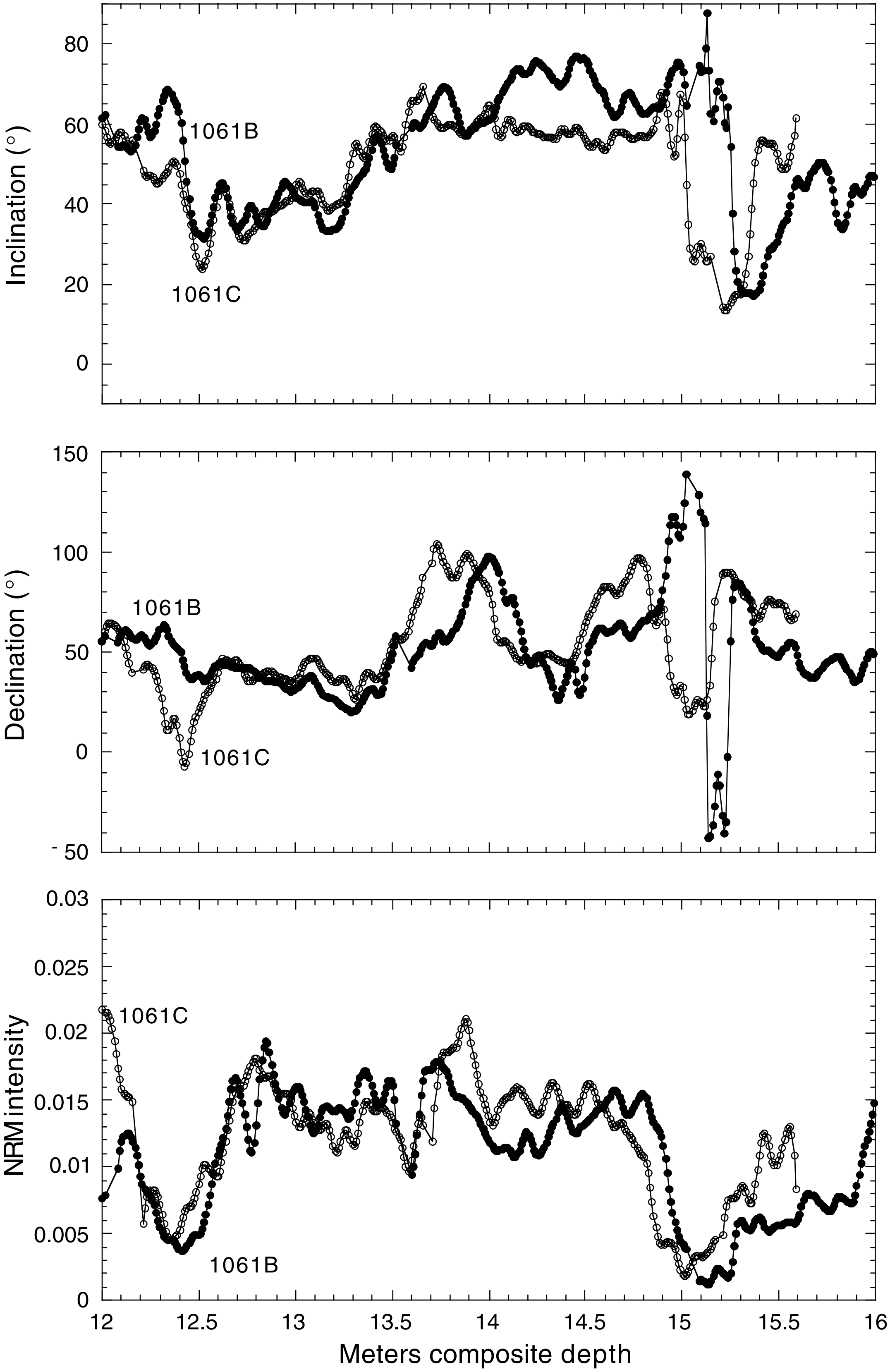

Figure F9. Paleomagnetic records of the Laschamp Excursion determined from discrete sample paleomagnetic studies of piston cores collected near Sites 1061 (JPC14, Blake Outer Ridge) and 1063 (CH89-9P, Bermuda Rise).

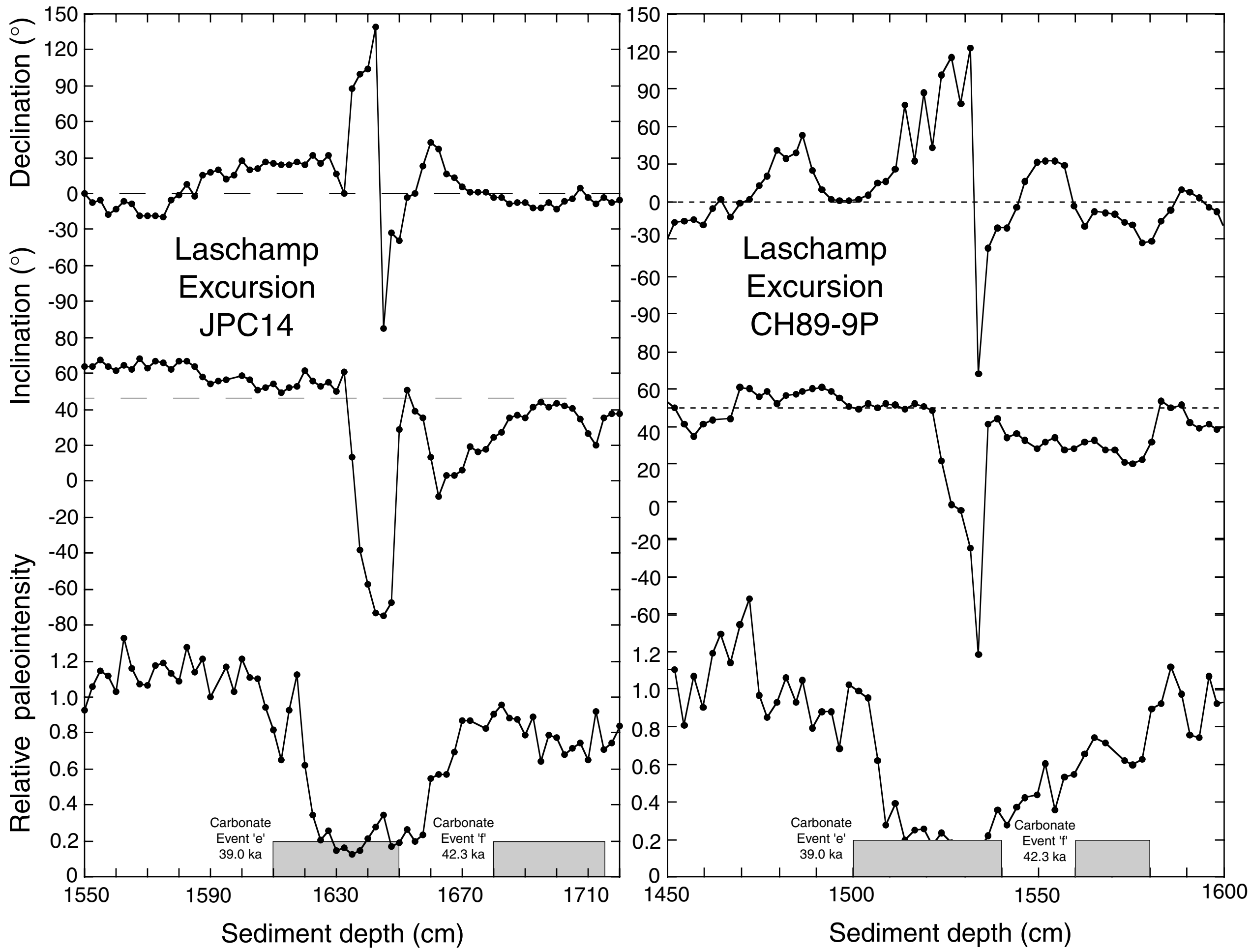

Figure F10. Map of the Blake/Bahama Outer Ridge showing bulk sediment accumulation rates (in centimeters per thousand years [cm/k.y.]) for the last 71,000 yr (Stages 1–4). Locations of Site 1061, Site 1062, core CH88-10P, and core JPC14 are also indicated.