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10. BRUNHES CHRON MAGNETIC FIELD EXCURSIONS RECOVERED FROM LEG 172 SEDIMENTS[1]

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ABSTRACT

During Ocean Drilling Program Leg 172, we recovered long-core paleomagnetic records of 14 "plausible" magnetic field excursions within the Brunhes Chron at Sites 1060–1063, separated by more than 1200 km. New U-channel paleomagnetic studies of all 14 excursions indicate that 12 have true excursional directions and are almost certainly "real" geomagnetic field excursions, but five excursions still require discrete sample paleomagnetic measurements to further replicate these results. U-channel measurements for two of the original 14 "plausible" excursions (3α and 5α) did not show evidence of true excursional directions and are no longer considered real. U-channel measurements also identified one new excursion not identified during shipboard measurements. We also identified other types of anomalous directional variability that we currently think may be due to systematic biases in the long-core and U-channel measurement process. Further study using discrete samples will be necessary to resolve such uncertainties. All of these observations suggest that excursions are not rare, random perturbations of the stable geomagnetic field, but rather an important systematic and distinct component of the Earth's magnetic field variability between field reversals.

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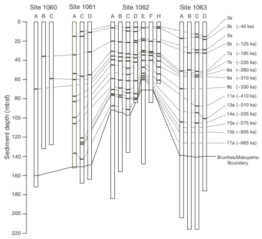
INTRODUCTION

During Ocean Drilling Program (ODP) Leg 172, ~6 km of Pliocene/Pleistocene deep-sea sediments was recovered from three sediment 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 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 mechanically undisturbed cores of soft sediment. During ODP Leg 172, 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-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 intensities) for the Brunhes Chron and identify 14 "plausible" Brunhes-aged magnetic field excursions (Fig. F1; Table T1) (Lund et al., 1998; Keigwin, Rio, Acton, et al., 1998). This number of excursions is larger than all previous good-quality Brunhes excursions noted worldwide.

F1. Summary of the Brunhes-aged magnetic field excursions, p. 8.



This paper summarizes new paleomagnetic and rock magnetic results derived from U-channel measurements of more than 150 m of Brunhes-aged sediment collected from Sites 1060–1063. These results confirm the existence of 12 of the 14 originally defined excursions. They also identify one new excursion not previously noted in the long-core measurements. Comparison of the U-channel and long-core measurements indicates that long-core measurements, on the whole, can almost always identify paleomagnetic secular variation (PSV) and excursions, but biases in the measurements are present that slightly alter the true paleomagnetic record (as defined by U-channel and selected discrete sample measurements). In a few unusual cases associated with low intensity natural remanent magnetization (NRM) or fast directional changes, the long-core results are significantly different from U-channel or discrete sample measurements.

T1. Summary of paleomagnetic evidence, p. 18.

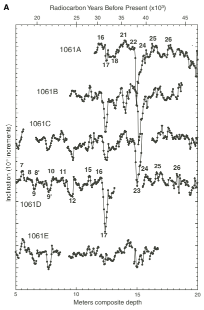
DIRECTIONAL SECULAR VARIATION DURING THE BRUNHES CHRON

Records of magnetic field secular variation within Leg 172 cores were routinely recovered aboard ship by measuring the 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 string magnetic overprint that has been noted previously during many ODP legs (e.g., Nagy and Valet, 1993; Weeks et al., 1993). Further AF demagnetization of selected core segments always 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).

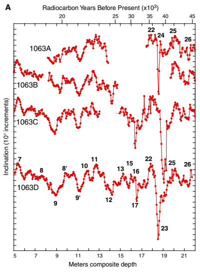
The patterns of directional variability observed after demagnetization could commonly be correlated between holes at individual sites for

Sites 1060–1063. For example, inclination and declination variability at Site 1061 (Blake Outer Ridge; five holes) between ~15,000 and 45,000 radiocarbon years before present (BP) is shown in Figure F2; similar variability at Site 1063 (Bermuda Rise; four holes) is shown in Figure F3. The chronologies for these selected intervals are based on radiocarbon dates associated with other nearby piston cores (Keigwin and Jones, 1994) that were correlated to the Leg 172 cores using variations in magnetic susceptibility (Keigwin, Rio, Acton, et al., 1998; see also Schwartz et al., 1997). It is clear for both sites that selected inclination and declination features can be traced among the records from independent holes separated by distances of <1 km. The most diagnostic features are narrow intervals of relatively low or high inclination or easterly or 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.

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

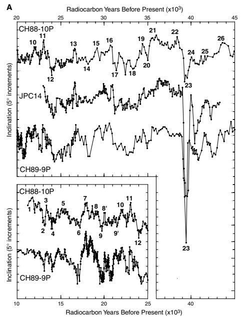


F3. Long-core inclination and declination measurements, Site 1063, p. 11.



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 within the same time interval (~15,000–45,000 radiocarbon years BP) as recorded at Site 1063 (Fig. F3) vs. Site 1061 (Fig. F2). The numbers that identify selected PSV features in Figures F2 and F3 are based on previously published piston-core studies (discrete sample measurements) from the same region (Lund, 1993; Lund et al., 1995, in press) summarized in Figure F4. Selected longer duration (10^4–10^5 yr) variations in the interval average inclination can also be correlated between sites (Keigwin, Rio, Acton, et al., 1998). Such variations are interpreted to indicate nonstationarity (time-dependent changes in the statistical character) of local secular variation.

F4. Discrete sample inclination and declination measurements from three piston cores, p. 13.



EXCURSIONS DURING THE BRUNHES CHRON

Our long-core paleomagnetic measurements (Lund et al., 1998; Keigwin, Rio, Acton, et al., 1998) indicated that at least 14 “plausible” magnetic field excursions have occurred over the past 780 k.y. during a time of apparently stable normal magnetic field polarity (Brunhes Chron). The “plausible” excursions were identified on the basis of three criteria: (1) presence of true excursional directions (virtual geomagnetic poles [VGPs] more than 45° away from the North Geographic Pole after reorienting core-segment average declinations to 0°), (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. (Two other potential excursions were identified that fail these criteria and were therefore not considered “plausible.” Another one or two potentially “plausible” but unnumbered excursions are located just above the Brunhes/Matuyama Boundary and are considered elsewhere in the context of the transitional field behavior.)

We temporarily named the 14 “plausible” excursions by the SPECMAP oxygen isotope stage within which they occur (Stages 3–15) and their relative sequence within a single oxygen isotope stage (α = younger, β = older; symbols “a” and “b” were used in Keigwin, Rio, Acton, et al. (1998) and Lund et al. (1998) but are changed herein to minimize conflict with SPECMAP substage names “a–e”). The stratigraphy of all identified Brunhes-aged excursions (>100 individual records) is shown in Figure F1. It is clear that individual excursions are not always noted in all holes. This is partially due to four limitations of long-core measurements and the coring process: (1) smearing of some sediment along the sides of the cores, (2) integration of paleomagnetic measurements over ~10 cm of sediment (a function of the magnetometer configuration), (3) limited demagnetization of the sediments (typically only up to 20 mT AF), and (4) coring gaps.

Previous paleomagnetic studies of piston cores from near the locations of Sites 1060–1063 (Lund et al., 1995, in press) identified three of the excursions noted in Figure **F1:** 3β (Laschamp Excursion), 5β (Blake Event), and 7α. Discrete sample measurements made during Leg 172 on sediments that record excursions 8α, 9α, 9β, and 11α confirm the long-core measurements but also illustrate the need for further detailed study of discrete and U-channel samples for all aspects of the observed field variability (Lund et al., 1998; Keigwin, Rio, Acton, et al., 1998).

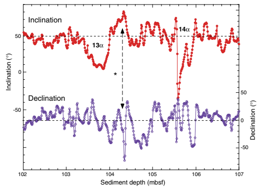
We now have replicate U-channel records across all of the "plausible" excursions listed in Table **T1**. The U-channel measurements confirm the existence of 12 of the excursions and noted a new one (17α) not identified in the long-core measurements. U-channel measurements contained no evidence of true excursional directions for excursions 3α and 5α; we now consider them not to be true excursions but rather artifacts of our analysis using long-core measurements alone. A U-channel study of the 3α and 3β excursion sequence is presented as a companion paper in this volume (Lund et al., **Chap. 11,** this volume).

Selected U-channel records of excursions 13α, 14α, 15α, 15β, and 17α are shown in Figures **F5**, **F6**, and **F7**. Excursions 14α and 15β look very similar to the pattern noted in shipboard long-core measurements. They both contain strongly negative inclinations, significant declination variability, and excursional VGPs. By contrast, excursions 13α and 15α are more subdued in directional variability than was expected from the long-core measurements. Their overall variability is still distinctive, but further analysis of the replicate U-channel records plus discrete sample measurements will be needed to state certainly whether or not these are true excursions as opposed to exceptionally large-amplitude secular variations (as noted in Table **T1**).

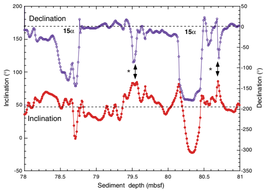
One complication, which we noted in both the long-core and U-channel measurements, is the presence of intervals with very high positive inclinations (>80°), often with large declination variability, which have excursional VGPs. Several such intervals are noted in Figures **F5**, **F6**, and **F7**. We noticed this first aboard ship during long-core measurements, and in several instances we could ascribe the effect to narrow intervals with distinctive lithology and anomalously high or low NRM intensity. The same effect is apparent in the U-channels. Up to now, we have presumed that such features are all artifacts of long-core or U-channel measurement and do not reflect true geomagnetic field variability.

Nevertheless, it is important to note that the Mono Lake Excursion (Denham and Cox, 1971; Liddicoat and Coe, 1979) does clearly have excursional VGPs associated with very high (~84°) positive inclinations. Unfortunately, it is the only example we currently have of "true" excursional behavior with high inclinations; all other previously published excursions (almost all from sites in the Northern Hemisphere) have excursional VGPs associated with intervals of negative inclination. Up to now, we have not assigned any "plausible" excursions to intervals of unusually high positive inclination but we clearly do note such intervals (Fig. **F5**, **F6**, and **F7**). In most cases, we are reasonably certain they are artifacts of continuous paleomagnetic measurement. However, ex-

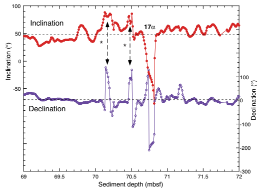
F5. U-channel inclination and declination results for the interval of excursions 13α and 14α, Hole 1063C, p. 15.



F6. U-channel inclination and declination results for the interval of excursions 15α and 15β, Hole 1062D, p. 16.



F7. U-channel inclination and declination results for the interval of excursion 17α, Hole 1062E, p. 17.



cursion 17α looks very similar in style to the Mono Lake Excursion and may indeed have excursional VGPs at times of high positive inclinations. Unfortunately, we currently do not have any unique way to confidently identify excursions associated with high positive inclinations on the basis of long-core or U-channel measurements. The only way we will ever confidently prove whether selected high-inclination intervals are truly excursional will be through discrete sample measurements that are planned for the future.

DISCUSSION

This overview of new U-channel paleomagnetic results from Leg 172 further supports our new view of geomagnetic field variability during the Brunhes Chron. It also illustrates the ability of ODP to acquire state-of-the-art paleomagnetic field records from deep-sea sediments using the APC and, within definable limitations, to initially evaluate the sediment paleomagnetism using the shipboard cryogenic magnetometer. U-channel measurements indicate, however, that selected secular variation or excursional features noted in the long-core measurement processes may be artifacts of the measurement process and require careful analysis and corroboration.

The number and ages of the Brunhes excursions listed in Table T1 suggest that excursions can no longer be viewed as simply or even primarily regional anomalies of the geomagnetic field. Within one small region, we have identified more Brunhes-aged excursions than all previous good-quality paleomagnetic studies worldwide put together. Moreover, for almost any previously identified excursion anywhere in the world, we can find an excursion record in Sites 1060–1063 that is not significantly different in age. This suggests that excursion intervals are broadly synchronous on a global scale, which in turn implies that the geomagnetic field is globally in an "excursional state" during these intervals.

Most of the excursions tend to occur in "bundles" of two or three close together with intervening intervals of distinctive (large amplitude) magnetic field secular variation. Altogether, the bundles tend to last 20–50 k.y. It is possible that these bundles of closely spaced excursions indicate a continuing "excursional state" or pattern in the core dynamo process that spans the duration of the bundles. Although each individual excursion probably contains only 1–2 k.y. of true excursional directions, the bundle time intervals, including the intervening distinctive secular variation, may all together represent more than 20% of Brunhes time.

All of these observations suggest that excursions are not rare, random perturbations of the stable geomagnetic field, but are rather an important systematic and distinct component of the Earth's magnetic field variability between field reversals. Based on our new results and previous studies, such an "excursional state" of the Earth's magnetic field may have both a strongly multipolar spatial pattern of variability and a complicated temporal pattern of variability. If this perspective is true, identification and correlation of individual excursion records on a global scale must depend on independent high-resolution age estimates; also, the detailed behavior of individual excursions may be quite different in different parts of the Earth. However, the exact space-time pattern of geomagnetic field behavior during excursional states and the relationships between individual excursions worldwide in any one narrow time interval must await further work and comparison with other global records.

CONCLUSIONS

During Leg 172, we recovered paleomagnetic records of 14 "plausible" magnetic field excursions at Sites 1060–1063 spanning more than 1200 km. New U-channel paleomagnetic studies of all 14 excursions indicate that 12 do contain true excursional directions, but five still require discrete sample paleomagnetic measurements to further verify their reality. U-channel measurements for two of the original 14 "plausible" excursions (3α, 5α) did not show evidence of true excursional directions and are no longer considered to be real. U-channel measurements also identified one new excursion not identified during shipboard measurements. We also identified other types of anomalous directional variability that we currently think may be due to systematic biases in the long-core and U-channel measurement process. Further study using discrete samples will be necessary to resolve such uncertainties. All of these observations suggest that excursions are not rare, random perturbations of the stable geomagnetic field, but rather an important systematic and distinct component of the Earth's magnetic field variability between field reversals.

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Figure F1. A summary of the Brunhes-aged magnetic field excursions identified at Sites 1060–1063. Individual excursion records (black intervals) were estimated by long-core paleomagnetic measurements and correlated and dated on the basis of magnetic susceptibility variations and inferred oxygen isotope stratigraphy (Keigwin, Rio, Acton, et al., 1998).

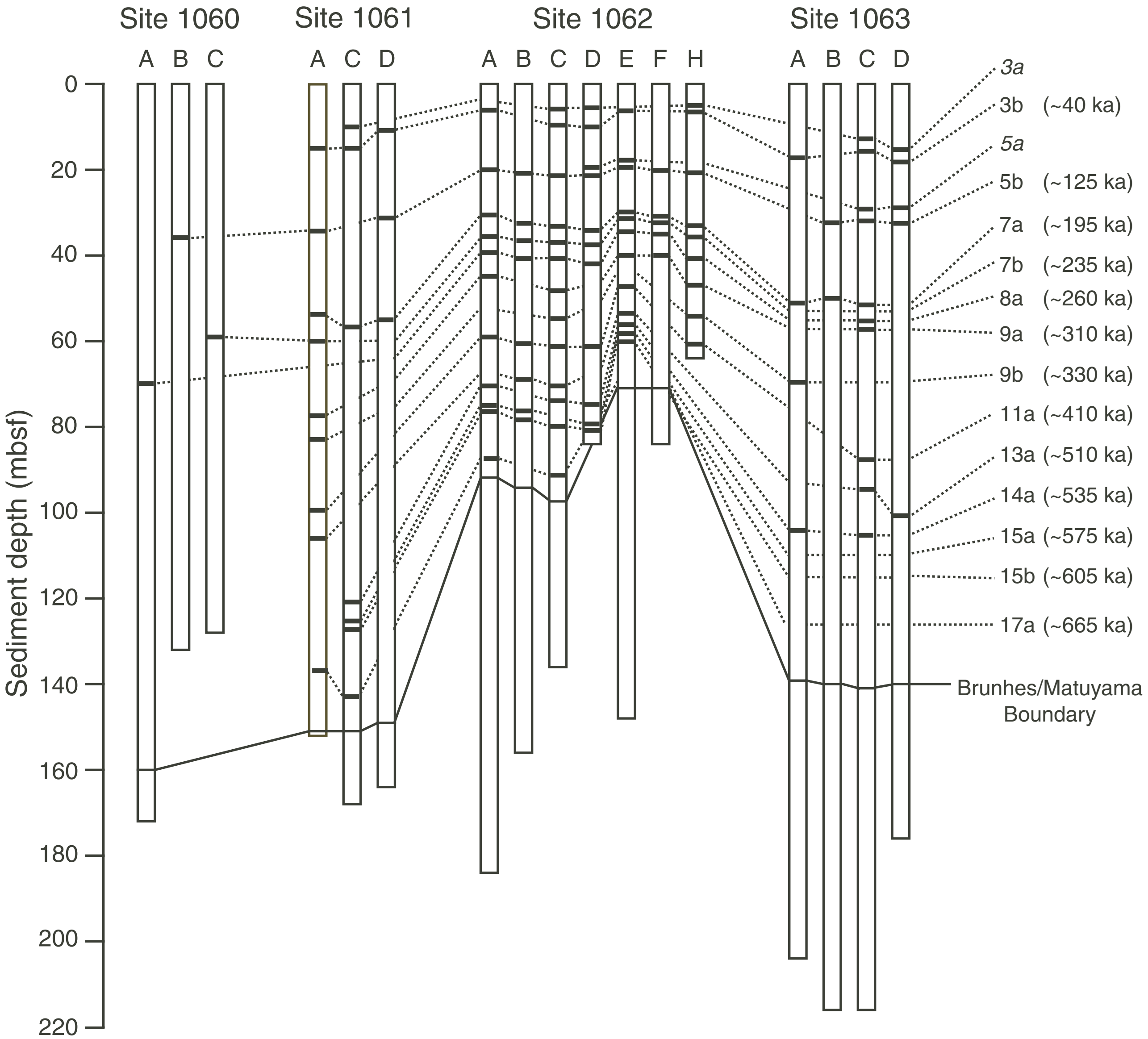

Figure F2. A. Long-core inclination for all five holes at Site 1061 (Blake Outer Ridge). Selected inclination and declination features are numbered for comparison with similar features in Figures F3, p. 11, and F4, p. 13. (Continued on next page.)

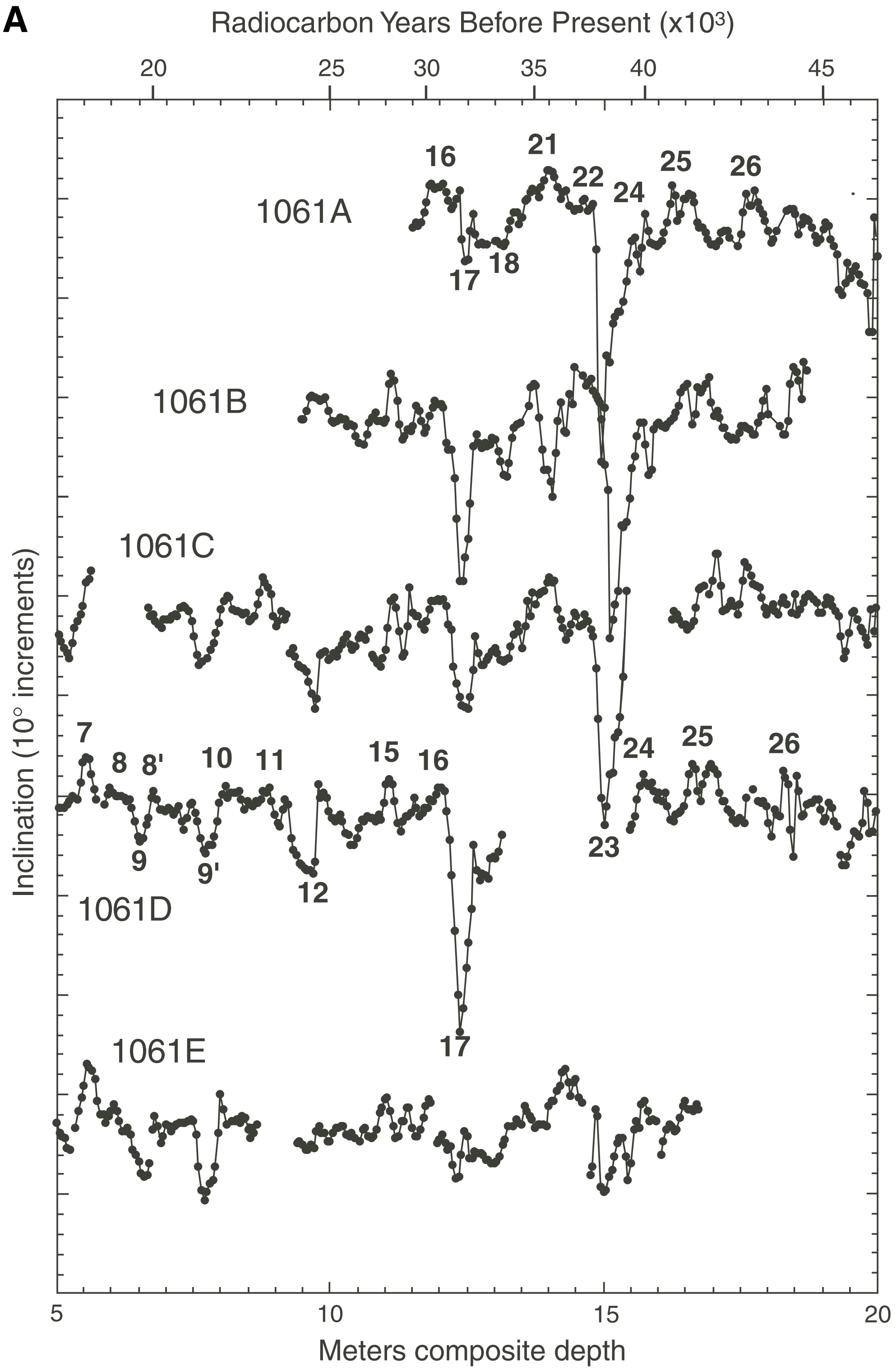

Figure F2 (continued). B. Declination measurements (20-mT AF demagnetization) at Site 1061.

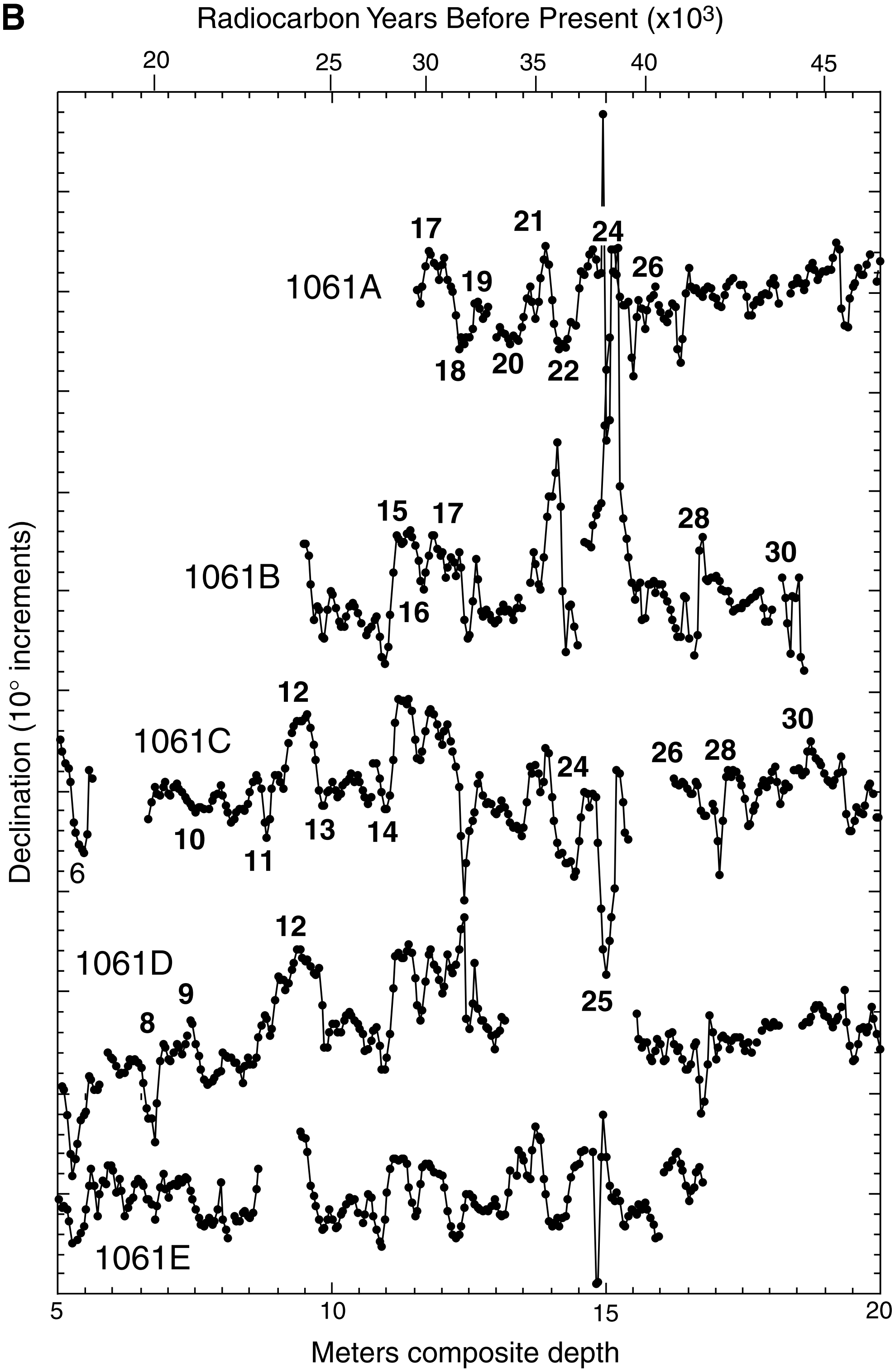

Figure F3. A. Long-core inclination measurements for all four holes at Site 1063 (Bermuda Rise). Selected inclination and declination features are numbered for comparison with similar features in Figures F2, p. 9, and F4, p. 13. (Continued on next page.)

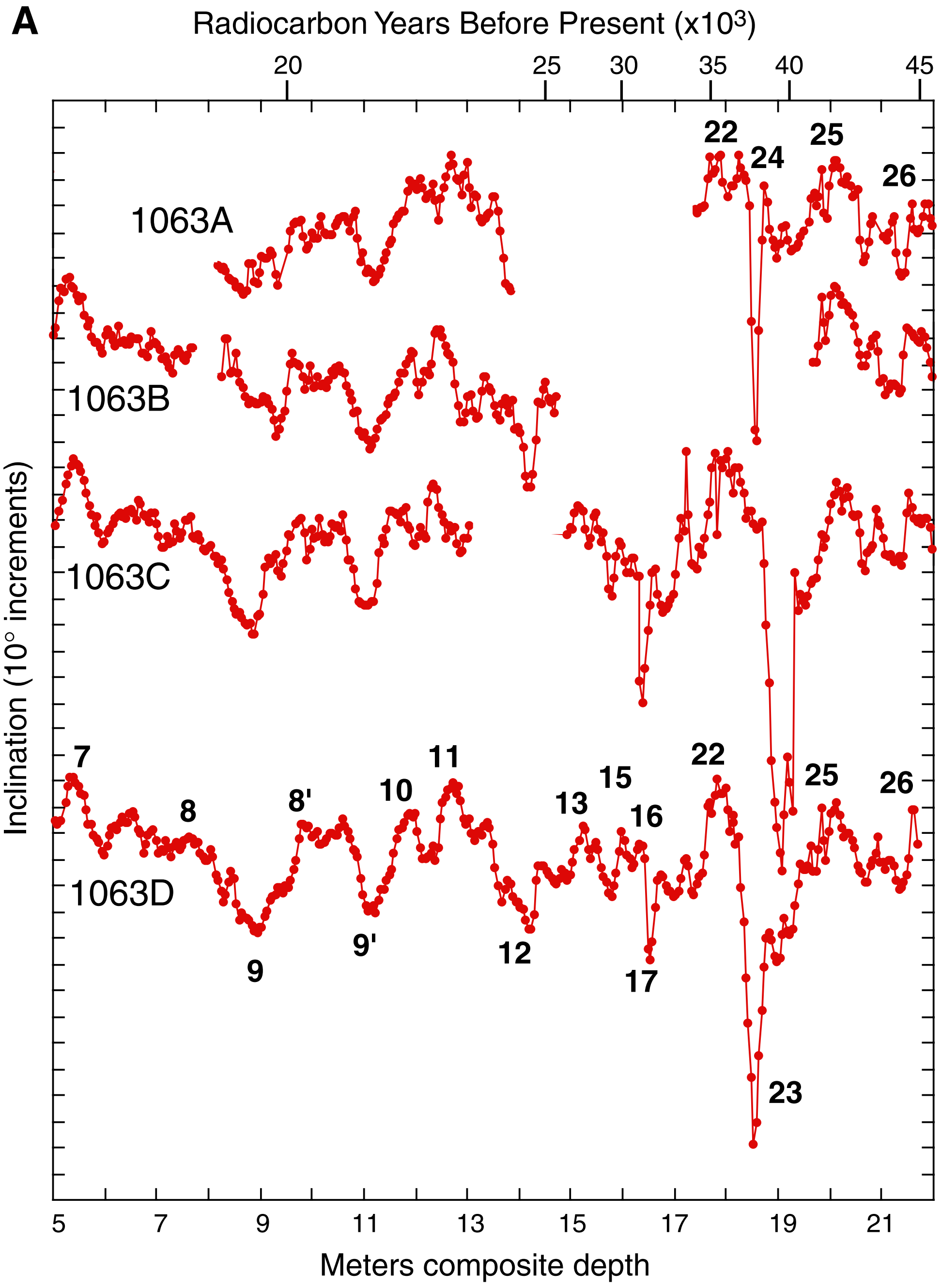

Figure F3 (continued). **B.** Declination measurements (20-mT AF demagnetization) at Site 1063.

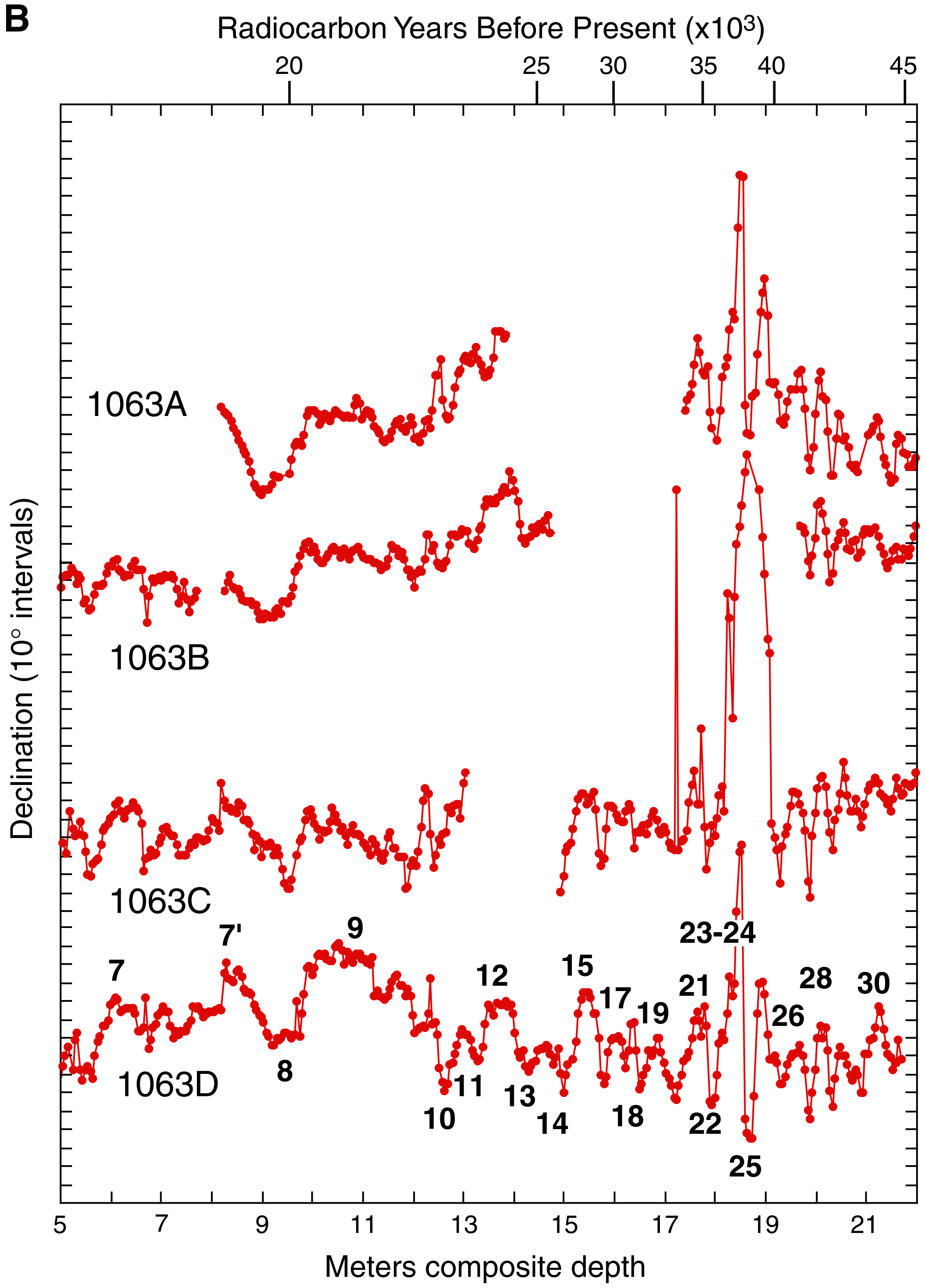

Figure F4. A. Discrete sample inclination measurements (Lund, 1993; Lund et al., in press) from three piston cores from the Blake Outer Ridge (CH88-10P, JPC14) and Bermuda Rise (CH89-9P). Selected inclination and declination features are numbered for comparison with similar features in Figures F2, p. 9, and F3, p. 11. The chronology for these cores is based on radiocarbon dates from Keigwin and Jones (1994) that were transferred to these cores based on correlations of magnetic susceptibility and calcium carbonate variability. (Continued on next page.)

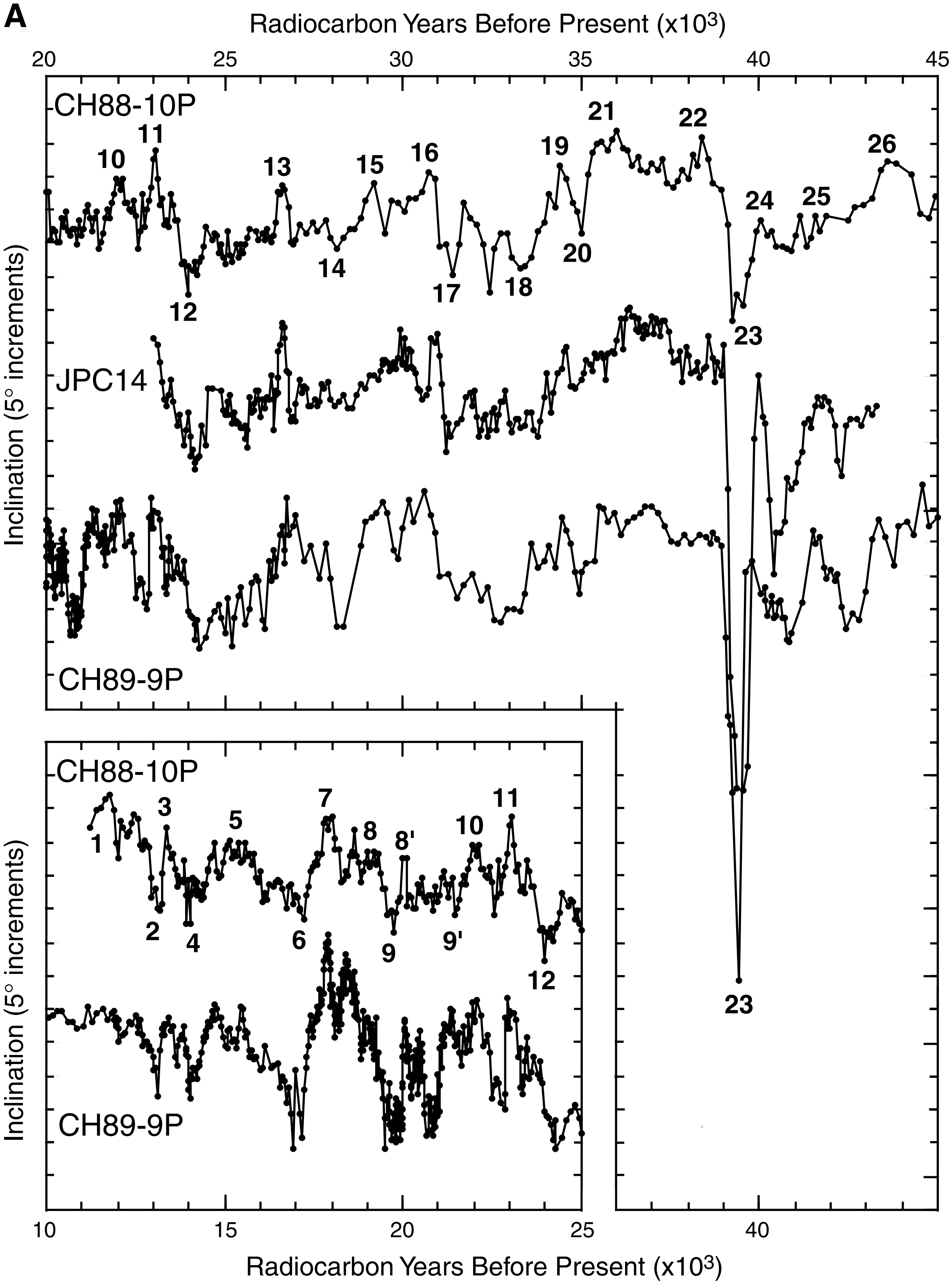

Figure F4 (continued). B. Declination measurements from Blake Outer Ridge and Bermuda Rise.

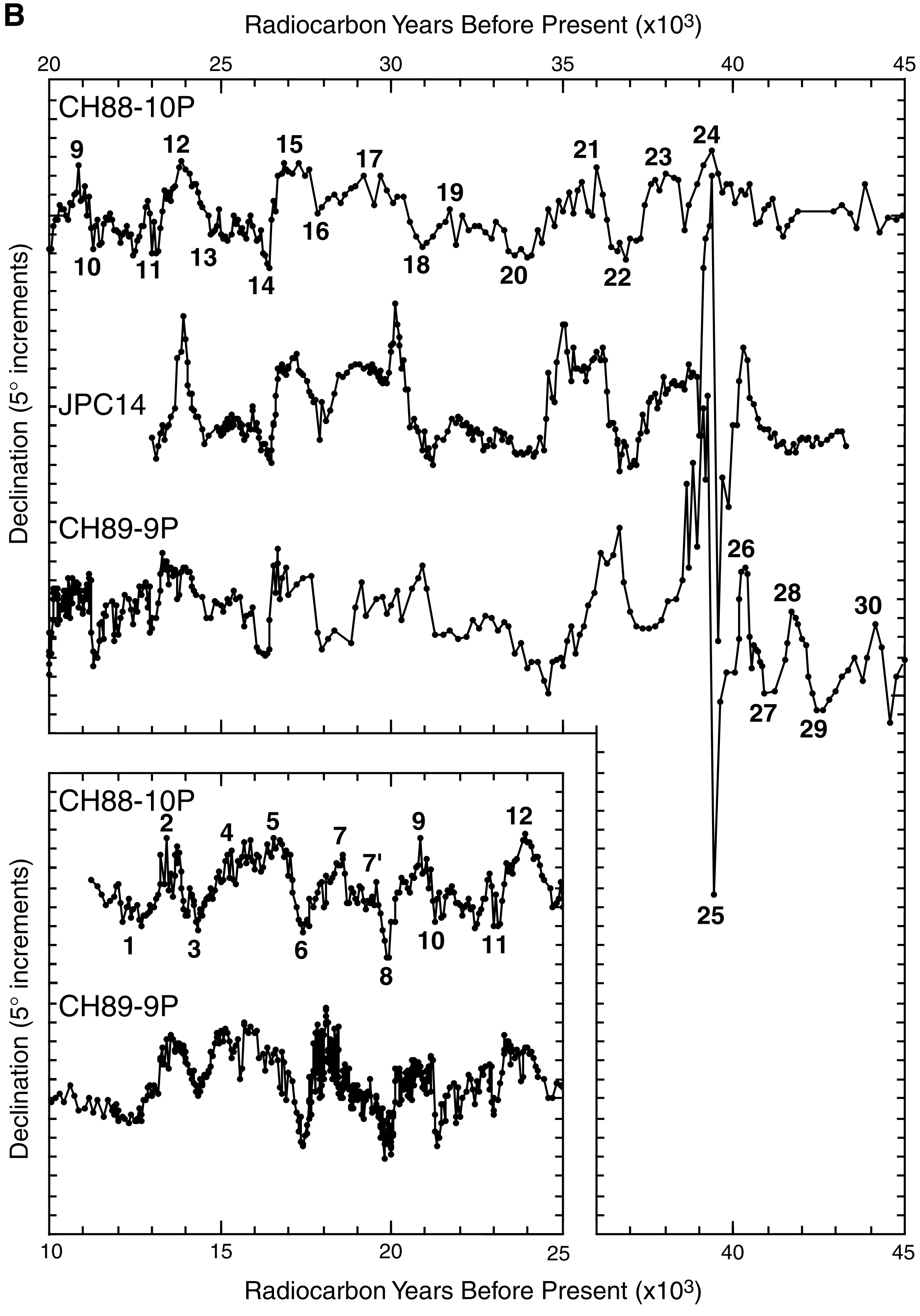

Figure F5. U-channel inclination and declination results (40-mT AF demagnetization) for the interval of excursions 13α and 14α in Hole 1063C. The starred horizon is one of several intervals of anomalously high positive inclinations discussed more fully in **"Excursions during the Brunhes Chron,"** p. 3.

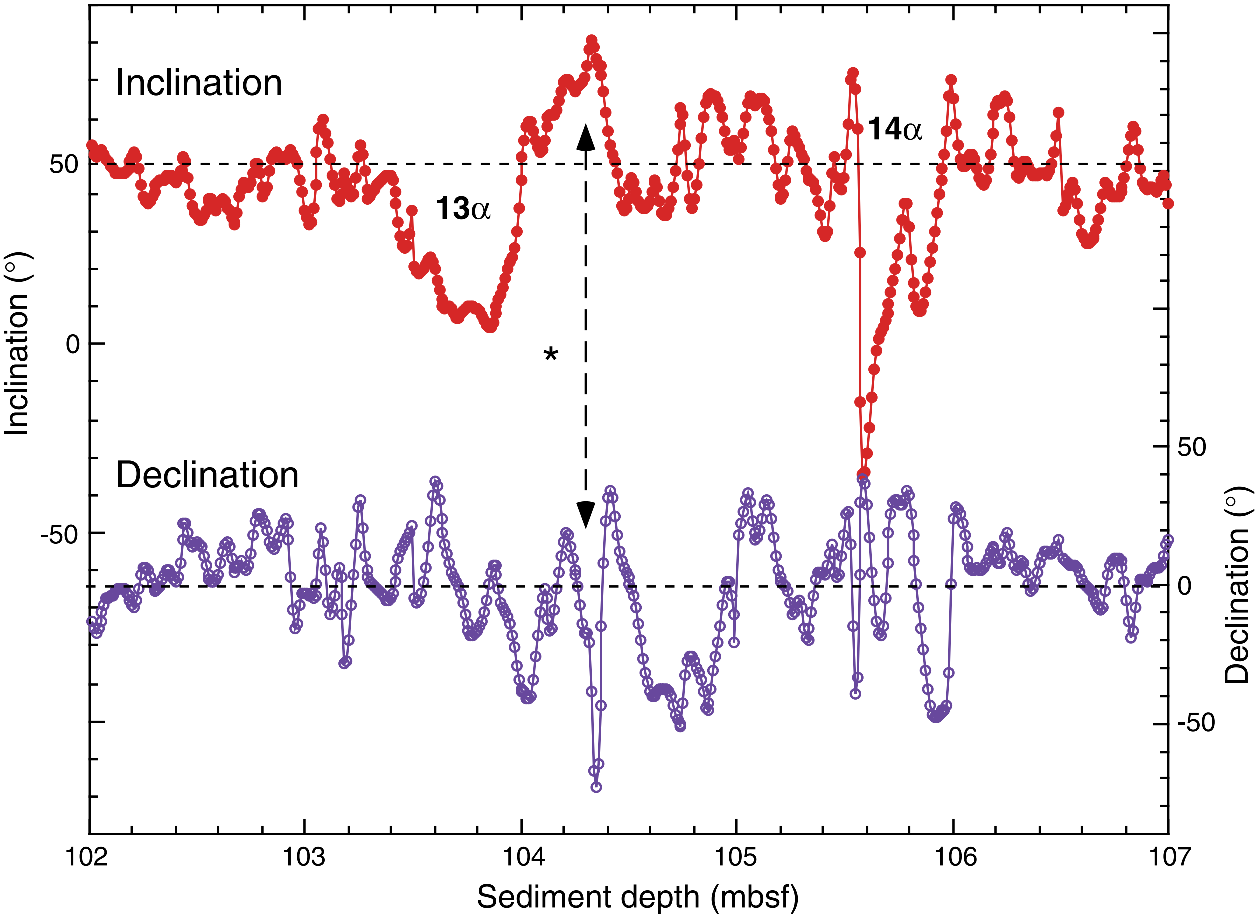

Figure F6. U-channel inclination and declination results (20-mT AF demagnetization) for the interval of excursions 15α and 15β in Hole 1062D. The starred horizons are representative of several intervals of anomalously high positive inclinations discussed more fully in **"Excursions during the Brunhes Chron,"** p. 3.

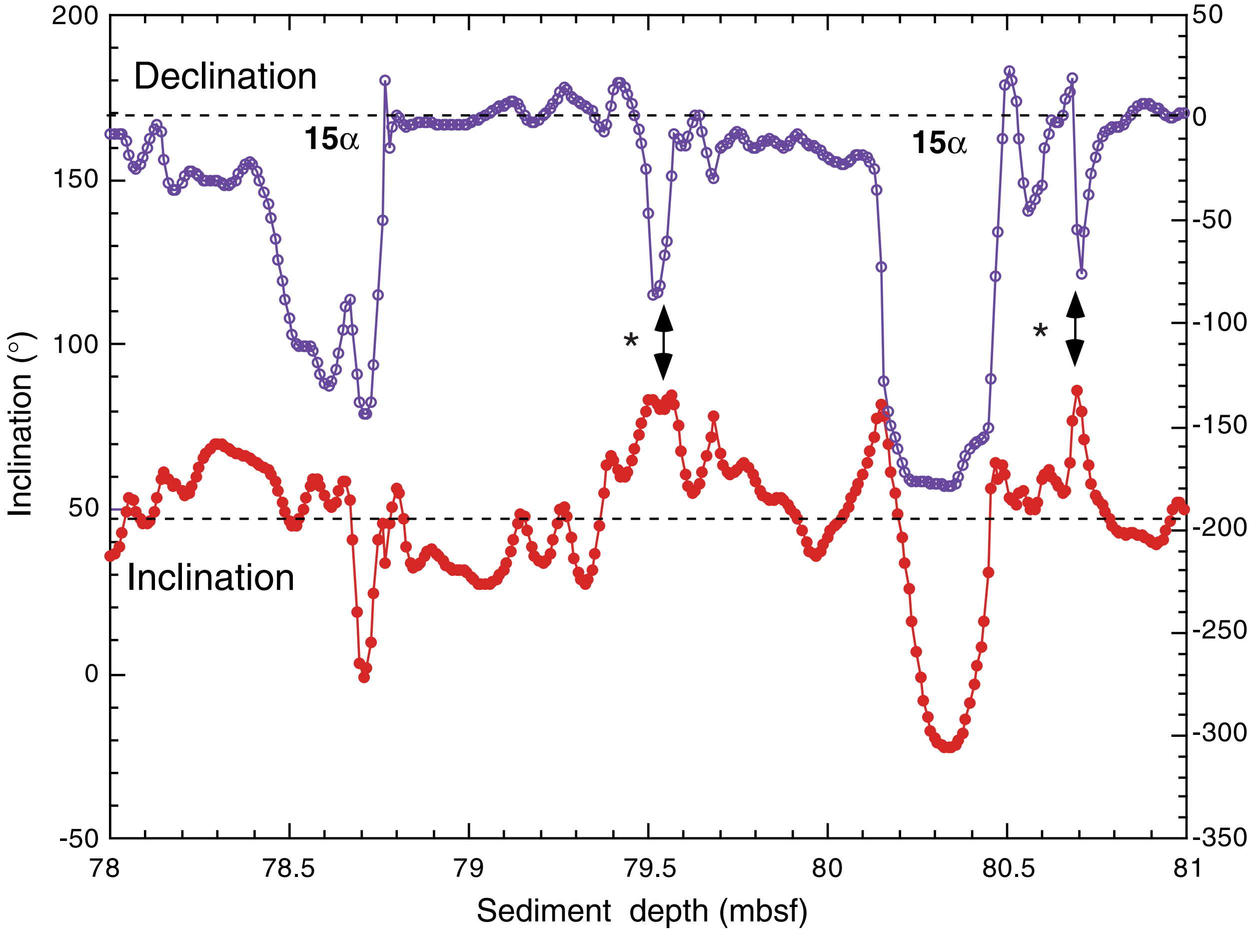

Figure F7. U-channel inclination and declination results (40-mT AF demagnetization) for the interval of excursion 17α in Hole 1062E. The starred horizons are representative of several intervals of anomalously high positive inclinations discussed more fully in "Excursions during the Brunhes Chron," p. 3.

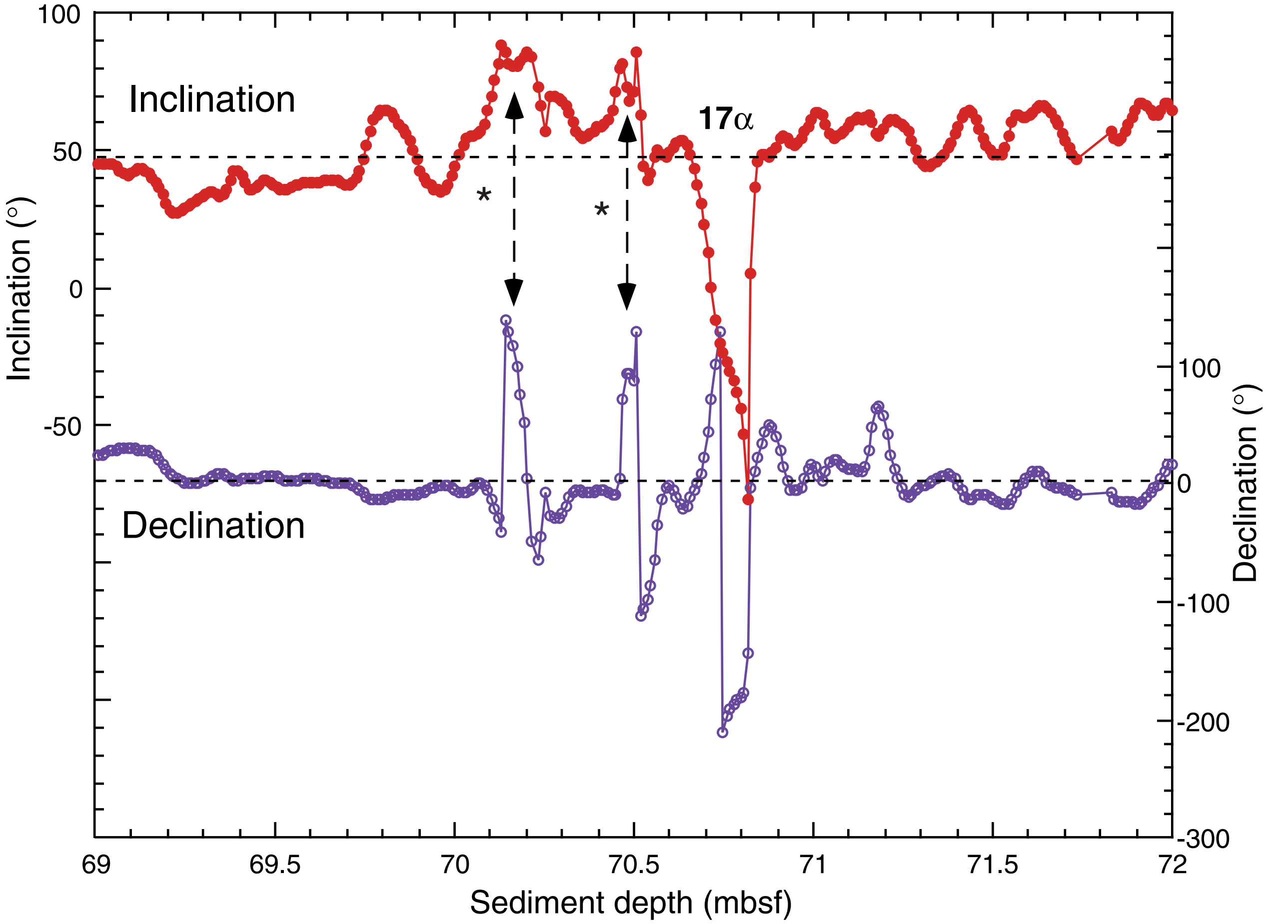

Table T1. Summary of paleomagnetic evidence for the existence and age of Brunhes Chron excursions recovered during Leg 172 and its site survey cruise.

Excursion	SPECMAP oxygen isotope stage	Age (ka)	Long-core measurement	U-Channel measurement	Discrete sample measurement
3a	*3*		*YES*	*NO*	*NO*
3β	**3**	**39–40***	**YES**	**YES**	**YES**
5a	*5*		*YES*	*NO*	*NO*
5β	**5.5**	**119–126**	**YES**	**YES**	**YES**
7α	**7.1**	**~194**	**YES**	**YES**	**YES**
7β	7.5	~236	YES	YES	
8α	**8.3**	**~258**	**YES**	**YES**	**YES**
9α	**8.5/9.1**	**~287/~309**	**YES**	**YES**	**YES**
9β	**9.3**	**~328**	**YES**	**YES**	**YES**
11α	**11.3**	**~406**	**YES**	**YES**	**YES**
13α	13.2	~510	YES	YES (PSV?)	
14α	14.2	~536	YES	YES	
15α	15.1	~573	YES	YES (PSV?)	
15β	15.4	~604	YES	YES	
17α	17.1	~666	YES	YES	

Notes: SPECMAP oxygen isotope stage and age assignments are summarized in Keigwin, Rio, Acton, et al. (1998). Excursions in bold type are those most trustworthy; these have been replicated in long-core, U-channel, and discrete sample measurements at multiple sites. Excursions in italics are no longer considered to be real excursions. * = radiocarbon age estimate from Lund et al. (in press). PSV = paleomagnetic secular variation.