Tiedemann, R., Mix, A.C., Richter, C., and Ruddiman, W.F. (Eds.)
Proceedings of the Ocean Drilling Program, Scientific Results Volume 202

2. Late Quaternary Paleomagnetic Secular Variation and Chronostratigraphy from ODP Sites 1233 and 1234[1]

Steve P. Lund,[2] Joseph Stoner,[3] and Frank Lamy[4]

ABSTRACT

During Ocean Drilling Program Leg 202, detailed shipboard paleomagnetic measurements at Sites 1233 and 1234 identified a reproducible high-resolution record of paleomagnetic secular variation (PSV) at each site. These records also contained evidence for three magnetic field excursions. This paper summarizes the complete paleomagnetic record from Site 1233 and the paleomagnetic record for the uppermost 30 meters from Site 1234. We also establish a detailed PSV correlation between the two sites, located ~500 km apart. Twenty-seven accelerator mass spectrometry radiocarbon dates permit us to develop time-depth plots and detailed PSV time series for the last ~50,000 yr at both sites. Based on our chronostratigraphy, the most recent excursions occur at ~35,000 cal. yr before present (BP) (Excursion 3α) and ~41,000 cal. yr BP (Excursion 3β). The excursions were named for the oxygen isotope stages within which they occur. These two excursions are not significantly different in age from the Mono Lake Excursion and Laschamp Excursion. A third, older excursion, which has not yet been adequately dated, also occurs at Site 1233.

INTRODUCTION

Our knowledge of detailed geomagnetic field secular variation in the Southern Hemisphere is very limited during prehistoric times. A few

[1] Lund, S.P., Stoner, J., and Lamy, F., 2006. Late Quarternary paleomagnetic secular variation and chronostratigraphy from ODP Sites 1233 and 1234. *In* Tiedemann, R., Mix, A.C., Richter, C., and Ruddiman, W.F. (Eds.), *Proc. ODP, Sci. Results,* 202: College Station, TX (Ocean Drilling Program), 1–22. doi:10.2973/odp.proc.sr.202.208.2006
[2] Department of Earth Sciences, University of Southern California, Los Angeles CA 90089-0740, USA. slund@usc.edu
[3] School of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis OR 97331-5503, USA.
[4] GeoForschungsZentrum, Telegrafenberg, 14473 Potsdam, Germany.

Initial receipt: 4 November 2004
Acceptance: 23 February 2006
Web publication: 1 December 2006
Ms 202SR-208

leomagnetic studies have developed reproducible Holocene paleomagnetic secular variation (PSV) records from Australia (Barton and McElhinny, 1981; Constable and McElhinny, 1985), New Zealand (Turner and Lillis, 1994), Argentina (Creer et al., 1983; Gogorza et al., 2000, 2002), and Antarctica (Brachfeld et al., 2000), but there is no reproducible detailed record of PSV from the entire Southern Hemisphere prior to ~18 ka. A gridwork of such records is essential for better understanding the global space-time pattern of field variability between reversals. Such a detailed knowledge of space-time field variability is particularly necessary to properly test newer, more realistic dynamo models of field variability (e.g., Kono and Roberts, 2002; Wicht and Olson, 2004) and better evaluate the relationship between magnetic field excursions and normal secular variation (e.g., Lund et al., 2001).

During Leg 202, we recovered replicate high-resolution PSV records for the last ~70–150 ka from Sites 1233, 1234, and 1235 (Mix, Tiedemann, Blum, et al., 2003). We present here a summary of the shipboard PSV data from replicate holes at Sites 1233 and 1234 for the last 50,000 yr. The PSV records from both sites contain evidence for two magnetic field excursions that are coeval with the Mono Lake (Benson et al., 2003) and Laschamp (Lund et al., in press) excursions, observed in the Northern Hemisphere. We also correlate the PSV records from Sites 1233 and 1234 and note their strong similarity even though they are located ~500 km apart. Finally, we integrate 27 radiocarbon dates recovered from Site 1233 to develop a revised chronostratigraphy at Sites 1233 and 1234 for the last 50,000 yr.

PALEOMAGNETIC METHODS

Shipboard paleomagnetic measurements were made on all cores recovered during Leg 202. Individual cores, normally ~9.5 m in length, were cut into 1.5-m sections and split in half; each archive half was measured at 5-cm intervals on the shipboard 2-G Enterprises cryogenic magnetometer (Mix, Tiedemann, Blum, et al., 2003). The natural remanent magnetization (NRM) of each core segment was initially measured and then alternating-field (AF) demagnetization at one or two steps up to 25 mT was applied; the NRM was remeasured after each AF demagnetization step. Individual core segments were not demagnetized at higher AF because the archive halves were to be further sampled for more detailed paleomagnetic studies after the completion of Leg 202. The limited shipboard AF demagnetization up to 25 mT, however, did a good job of removing a strong but soft viscous overprint that is often noted in cores collected during Ocean Drilling Program (ODP) legs (Mix, Tiedemann, Blum, et al., 2003; Lund et al., 2003). More detailed paleomagnetic measurements have been made in three selected 1.5-m intervals using U-channels that were collected from the centers of archive core halves. These results, reported in a companion article (**Lund et al.,** this volume), corroborate the shipboard paleomagnetic measurements presented here.

All holes at each site have been correlated based on a variety of shipboard stratigraphic measurements and normalized to a common depth scale (meters composite depth [mcd]) for comparison (Mix, Tiedemann, Blum, et al., 2003). A composite splice section has been chosen from the replicate holes that best represents the observed variability at each site. These independent correlations were used to reconstruct the declination record at each site. The declination records have been modified by first rotating the average declination for each core to 0° and then slightly varying each core's average declination to best match the declination trends between adjacent cores from each hole based on the observed declination variability in the other holes using the splice correlations.

RESULTS

Site 1233 Paleomagnetic Secular Variation Records

The AF demagnetized paleomagnetic directional records from Holes 1233A–1233E (41.0°S, 74.45°W; 838 m water depth) are displayed in Figures F1, F2, F3, F4, and F5. The solid lines represent a seven-point running average of the directional data. Selected inclination (I1–I106) and declination features (D1–D111) are noted based on their appearance in records from multiple holes. Normally, directional features were replicated in at least three holes, but selected features (in parentheses) were only replicated in two holes. The boundaries between successive cores are evident in Figures F1, F2, F3, F4, and F5 as gaps in the directional records. The paleomagnetic directional record from the splice is shown at the left in Figures F1, F2, F3, F4, and F5. The splice directional record represents our best composite record of the PSV recorded at Site 1233, based on shipboard measurements.

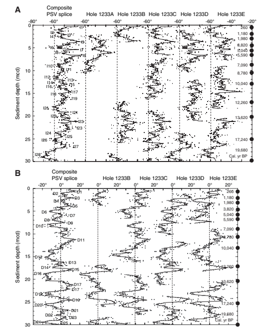
The inclinations at Site 1233 typically vary from –70° to –30° with an average near –55°. The observed average inclination is ~5° less than the expected axial-dipole inclination for the site latitude and ~10° less than the average inclination expected for this site based on long-term latitude-dependent nondipole effects (ΔI anomaly) (e.g., Lund, 1993; Merrill et al., 1996). The slightly lower than expected inclinations are probably a result of the presence of some residual viscous overprint (steep positive inclination) from coring as noted above (Mix, Tiedemann, Blum, et al., 2003; Lund et al., 2003). The limited U-channel measurements presented in Lund et al. (this volume) document 5°–10° steeper inclinations in the cleaned U-channel paleomagnetic results but show the same pattern of variability noted in the shipboard measurements presented here. The inclination variability displays a strong sense of cyclicity overall. The most common cyclicity occurs with a stratigraphic interval of ~1–2 m, but longer ~3- to 5-m cycles are also intermittently visible.

The declinations typically vary from –20° to +20° with an artificially imposed long-term average declination near 0°. The declination variability is higher between ~45 and 70 mcd, with 60°–70° declination swings being more common. This interval contains two magnetic field excursions, and the declinations display the same overall pattern of cyclicity noted for the inclinations above.

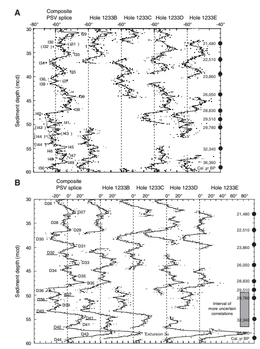
Radiocarbon age determinations and an estimated chronology for Site 1233 based on preliminary paleointensity measurements (Mix, Tiedemann, Blum, et al., 2003) suggest that Site 1233 has an average sediment accumulation rate of ~1.5 m/k.y. Based on this rate, the inclination and declination cyclicity duration ranges primarily from ~700 to 3500 yr. Such values are quite similar in amplitude and frequency to late Quaternary PSV observed in the Northern Hemisphere (e.g., Lund, 1993, 1996).

The inclinations and declinations also display six short intervals of significantly higher variability: (1) 57–59, (2) 66.5–69, (3) 95.5–99.5, (4)

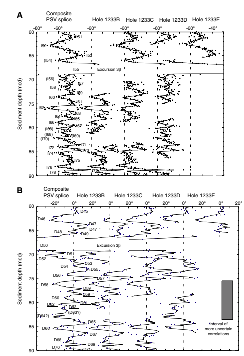
F1. Site 1233 PSV records, 0–30 mcd, p. 11.



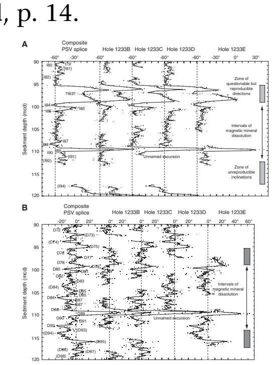
F2. Site 1233 PSV records, 30–60 mcd, p. 12.



F3. Site 1233 PSV records, 60–90 mcd, p. 13.



F4. Site 1233 PSV records, 90–120 mcd, p. 14.



109–110.5, (5) 112.5–117.5, and (6) 120–125 mcd. We believe that the directions in three of these intervals (95.5–99.5, 112.5–117.5, and 120–125 mcd) are anomalous because of coring or rock magnetic complications. The intervals at 95.5–99.5 and 120–125 mcd contain inclinations that reach almost reversed polarity and are reproducible in three holes. However, the declinations in both intervals are not at all anomalous, and rock magnetic evidence (Mix, Tiedemann, Blum, et al., 2003) indicates that these are intervals of extremely low NRM intensities. The third interval at 112.5–117.5 mcd has no reproducible inclination measurements, even though the declinations appear to be normal, and also occurs in an interval of extremely low NRM intensities. More detailed U-channel paleomagnetic and rock magnetic measurements will be necessary to better understand the observed directional variability in these three intervals, but we now consider the directional variability to be an artifact of coring or rock magnetic complications rather than that of geomagnetic origin.

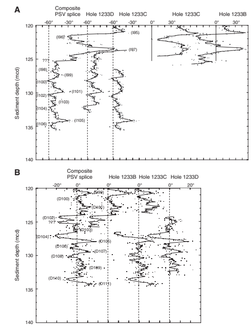
We believe that the directions in the other three intervals are of geomagnetic origin and represent magnetic field excursions. The declinations in the interval 57–59 mcd reproducibly undergo an ~90° swing to the east and a return to values near 0°, whereas the inclinations vary in a more normal manner. It is important to note that this anomalous declination swing is seen in all holes, which were separated by a total distance of at least 100 m. Our initial assessment was that the anomalous declinations were a sedimentologic artifact, perhaps caused by a local sediment slump or turbidite. However, this exact directional pattern is also seen at Site 1234, ~500 km away. The directions are truly excursional (virtual geomagnetic poles [VGPs] >45° from the North Geographic Pole) in the interval 57.5–58.5 mcd. The directions in the interval 66.5–69 mcd (Fig. F6) reproducibly undergo a complete magnetic field reversal that contains truly excursional directions within the entire interval. The onset of the excursion and almost complete reversal of polarity occurs within <50 cm, and directions maintain stable reversed polarity for more than a meter, finally returning to normal polarity with some significant oscillation in another meter. A similar full reversal occurs in the interval 109–110.5 mcd. All three excursion intervals occur within intervals of surrounding PSV that are reproducible among all holes at Site 1233.

Site 1234 Paleomagnetic Secular Variation Records

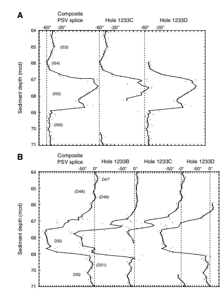
The AF-demagnetized paleomagnetic directional records for the uppermost 30 mcd in Holes 1234A–1234C (36.22°S, 73.68°W; 1015 m water depth) are shown in Figures F7 and F8. The solid lines represent a three-point running average of the directional data. Selected inclination (I1–I45) and declination features (D1–D47) are noted based on their appearance in records from at least two holes. The boundaries between successive cores are evident in Figures F7 and F8 as gaps in the directional records. The paleomagnetic directional record from the splice is shown at the left in Figures F7 and F8. The splice directional record represents our best composite record of the PSV recorded at Site 1234, based on shipboard measurements. Analysis of the lower portions of this site is continuing.

The inclinations at Site 1234 typically vary from –50° to –10° with an average near –40°. The observed average inclination is ~15° less than the expected axial-dipole inclination for the site latitude and ~20° less than the average inclination expected for this site based on long-term

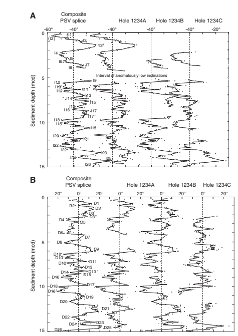
F5. Site 1233 PSV records, 120–140 mcd, p. 15.



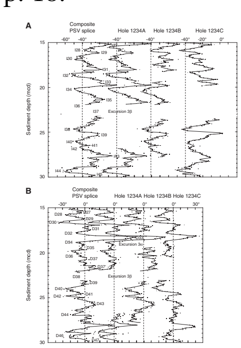
F6. Excursion 3β detail, Site 1233, p. 16.



F7. Site 1234 PSV records, 0–15 mcd, p. 17.



F8. Site 1234 PSV records, 15–30 mcd, p. 18.

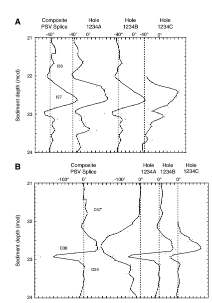


latitude-dependent nondipole effects (ΔI anomaly) (e.g., Lund, 1993; Merrill et al., 1996). The lower than expected inclinations are probably a result of the presence of some residual viscous overprint (steep positive inclination) from coring (Mix, Tiedemann, Blum, et al., 2003; Lund et al., 2003). Limited U-channel measurements from Site 1233 presented in **Lund et al.** (this volume) document 5°–10° steeper inclinations in the cleaned U-channel paleomagnetic results. The inclination variability displays a strong sense of cyclicity overall. The most common cyclicity occurs with a stratigraphic interval of ~0.5–1 m, but longer ~3-m cycles are also intermittently visible. The declinations typically vary from –20° to +20°, with an artificially imposed long-term average declination near 0°. The declinations display the same overall pattern of cyclicity shown for the inclinations.

Radiocarbon age determinations suggest that Site 1234 has an average sediment accumulation rate of 0.5–1.0 m/k.y. in the uppermost 30 mcd. On that basis, inclination and declination cyclicity duration at Site 1234 ranges primarily from ~1000 to 3000 yr, very similar to values noted at Site 1233. Such values are also quite similar in amplitude and frequency to late Quaternary PSV observed in the Northern Hemisphere (e.g., Lund, 1993, 1996).

The Site 1234 directions also display three short intervals of significantly higher variability: (1) 4.3–5, (2) 18–19, and (3) 22–23.5 mcd. The inclinations between 4.3 and 5 mcd vary dramatically in a nonreproducible manner, even though the declinations appear to behave normally. The NRM intensity in this interval is exceptionally weak (Mix, Tiedemann, Blum, et al., 2003), and we interpret these anomalous inclinations to be the result of rock magnetic complexities, most probably the continuing presence of a relatively strong viscous (positive inclination) overprint. The declinations between 18 and 19 mcd make a significant swing to the east (80° in Hole 1234A and 50° in Hole 1234C) before returning to values near 0°, whereas the inclinations vary in a more normal manner. Taken by itself, we might consider this to be some type of sedimentologic artifact; however, this pattern is very similar to the pattern shown at 57–59 mcd at Site 1233. Our correlations indicate that the overall pattern of variability surrounding 18–19 mcd in Site 1234 and 57–59 mcd in Site 1233 are correlative and likely represent a geomagnetic excursion. The directions in the third anomalous interval from 22 to 23.5 mcd make an almost complete polarity reversal (Fig. F9). The inclinations in all three holes reach almost +50° (full reversal), but the declinations in the three holes somewhat disagree with each other. Two of the declination records (Holes 1234B and 1234C) display an almost ±100° oscillation in declination around the imposed 0° baseline, whereas the declinations in Hole 1234C make a complete 180° reversal. We believe that these records represent a second excursion in the sequence, but there is significant residual overprint that prevents certainty in the exact pattern of excursional behavior. Detailed U-channel measurements will be required to better define the pattern of directional variability in this interval.

F9. Site 1234 PSV records, 0–15 mcd, p. 19.

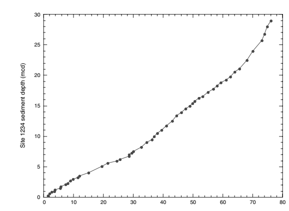


Correlation of Paleomagnetic Secular Variation from Sites 1233 and 1234

The similar scale of cyclicity at Sites 1233 and 1234 and their proximity (~500 km apart) both suggest that PSV correlations should be possible. To begin the correlation, we assumed that the excursional declination swing near 58 mcd at Site 1233 (D44/D43/D42) can be correlated with the similar excursional declination swing near 18 mcd at Site 1234 (D34/D33/D32). Similarly, we assumed that the larger interval of excursional directions near 68 mcd at Site 1233 (D51/D50/D49, I56/I55/I54) can be correlated with the second larger interval of excursional directions near 22.5 mcd at Site 1234 (D39/D38/D37, I38/I37/I36). Shipboard correlation of the Site 1233 paleomagnetic data and magnetic susceptibility to its site survey Core GeoB-3313-1 (Mix, Tiedemann, Blum, et al., 2003) and associated radiocarbon dates indicate that Site 1233 cores were recovered to within ~10 cm of the sediment/water interface. Correlation of Site 1234 paleomagnetic data and magnetic susceptibility to its site survey gravity Core RR9702A-41GC (S.P. Lund, unpubl. data) also indicate that the Site 1234 cores were recovered to within ~20 cm of the sediment/water interface. On that basis, we expected that the PSV in the uppermost 1–3 mcd at each site should generally correlate.

The actual correlation attempted to match specific inclination and declination peaks or troughs in the two records using the general tie points previously identified as a starting point. In all cases, the phase relationships noted between inclination and declination peaks or troughs at each site had to be preserved in the correlation to the other site. Ultimately, a table of all correlatable PSV features was developed. This table is available at **earth.usc.edu/~slund/data/index.php.** The depths of correlatable PSV features at Sites 1233 and 1234 are plotted in Figure **F10.** It is clear that Site 1234 has an average sediment accumulation rate in the uppermost 30 mcd that is only about one-third that of Site 1233.

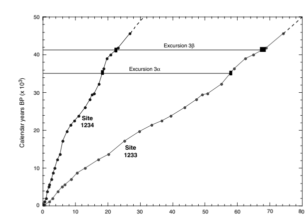
F10. Excursion 3β detail, Site 1234, p. 20.



Chronostratigraphy of Sites 1233 and 1234

A total of 20 accelerator mass spectrometry (AMS) radiocarbon dates have been recovered from Site 1233 (Lamy et al., 2004), and another seven AMS radiocarbon dates have been recovered from site survey Core GeoB-3313-1 and correlated to Site 1233 (Lamy et al., 2002; Mix, Tiedemann, Blum, et al., 2003). All 27 dates are plotted in Figures **F1, F2, F3, F4,** and **F5.** Time-depth plots for Sites 1233 and 1234 were developed using these dates (Fig. **F11**). These results suggest that the sediment accumulation rate at Site 1234 has been about one-third that of Site 1233 for the last 45,000 yr.

F11. PSV depth correspondence, p. 21.



The stratigraphic locations of the most recent excursions from Site 1233 and Site 1234 are also noted by small boxes. The two excursions occur at ~35,000 cal. yr before present (BP) and 41,000 cal. yr BP, both within oxygen isotope Stage 3. On that basis, we have initially named them Excursion 3α and 3β, respectively. This is consistent with the naming pattern developed by Lund et al. (2001) for the Brunhes-aged excursions for ODP Leg 172, named for the oxygen isotope stage within which they occur and the youngest excursion in each stage is labeled "α."

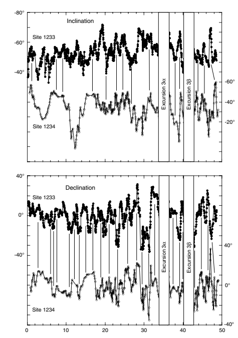
Lund et al. (1998, 2001) have argued that a global excursional state occurs intermittently during periods of stable magnetic polarity. During such states, it is common to have excursions occurring in many parts of the planet at essentially the same time, even though they may not have the same pattern of directional variability. Understanding the global space-time pattern of field behavior within and surrounding excursional states will be needed to assess how excursions from different parts of the planet relate to one another. Our new excursion records support that view. Excursion 3α at ~35,000 cal. yr BP is not significantly different in age from the Mono Lake excursion noted in western North

America (~32,000–34,000 cal. yr BP; Benson et al., 2003). Excursion 3β at ~41,000 cal. yr BP is not significantly different in age from the Laschamp excursion in the North Atlantic region, recently summarized by Lund et al. (in press), also at ~41,000 cal. yr BP.

It is important to note, however, that the directional variability for Excursions 3α and 3β at Sites 1233 and 1234 is significantly different in pattern from that of the Mono Lake and Laschamp excursions in the Northern Hemisphere. Excursion 3α is very unusual in that its anomalous directions are limited to a large (~90°) easterly swing in declination, unlike the oscillatory variation noted by Liddicoat and Coe (1979) at Mono Lake, California (USA). The directional morphology of Excursion 3β at Site 1233 is actually a full polarity reversal, whereas the Laschamp Excursion in the North Atlantic region (Lund et al., in press) has an oscillatory variability very similar to the Northern Hemisphere Mono Lake Excursion.

We can also use the new chronology to plot time series of the overall PSV from the Site 1233 and 1234 splices for the last 50,000 yr, as shown in Figure **F12.** It is clear that there are a large number of correlatable directional features between the two sites. Moreover, the PSV patterns surrounding the two excursions are strikingly similar, corroborating our initial assertion that the two excursion records at Sites 1233 and 1234 were the same. Even so, there are significant intervals in inclination, such as at ~5,000 and 15,000 cal. yr BP, where the records are quite different even though the declinations in those intervals compare well. We attribute this to the presence of some residual positive inclination overprint that has not been removed. We expect that U-channel paleomagnetic studies, which will include more careful AF demagnetization, will be necessary to recover more accurate PSV records from these two sites.

F12. PSV time series, p. 22.



CONCLUSIONS

The shipboard paleomagnetic records from Sites 1233 (entire 135 mcd) and 1234 (uppermost 30 mcd) are reproducible among all the holes at each site and can be generally correlated between sites for the last ~50,000 yr. The PSV patterns at both sites display directional cyclicity in the ~700–3500 yr range, which is consistent with patterns observable in the Northern Hemisphere for the same time interval. The inclination records, especially at Site 1234, show evidence for the continuing presence of some residual magnetic overprint (steep positive inclination) after 25-mT AF demagnetization, which makes the average inclinations anomalously low. This overprint may also be the cause of poorer PSV correlations between Sites 1233 and 1234 at ~5,000 and ~15,000 cal. yr BP.

A total of 27 AMS radiocarbon dates permitted us to develop time-depth curves for both sites over the last ~50,000 yr. The curves suggest that Site 1233 had sediment accumulation rates of ~1.5 m/k.y. for the last 50,000 yr, but the sediment accumulation rate at Site 1234 was only ~0.5 m/k.y. for the last 50,000 yr.

Both sites contain reproducible and correlatable evidence for two excursions at ~35,000 cal. yr BP (Excursion 3α) and ~41,000 cal. yr BP (Excursion 3β). These two excursions are not significantly different in age from the Mono Lake and Laschamp Excursions, respectively, but they appear to have distinctly different patterns of directional variability at

Sites 1233 and 1234. We also note clear indication of a third, older excursion at Site 1233, but we cannot yet date it with any certainty.

ACKNOWLEDGMENTS

This research used samples and data provided by the Ocean Drilling Program (ODP). ODP is sponsored by the U.S. National Science Foundation (NSF) and participating countries under the management of Joint Oceanographic Institutions (JOI), Inc. Funding for this research was provided by United States Science Support Program funds from NSF.

REFERENCES

Barton, C., and McElhinny, M., 1981. A 10,000 yr geomagnetic secular variation record from three Australian maars. *Geophys. J. R. Astron. Soc.,* 67:465–485.

Benson, L., Liddicoat, J., Smoot, J., Sarna-Wojcicki, A., Negrini, R., and Lund, S., 2003. Age of the Mono Lake excursion and associated tephra. *Quat. Sci. Rev.,* 22(2–4):135–140. **doi:10.1016/S0277-3791(02)00249-4**

Brachfeld, S., Acton, G.D., Guyodo, Y., and Banerjee, S.K., 2000. High-resolution paleomagnetic records from Holocene sediments from the Palmer Deep, western Antarctic Peninsula. *Earth Planet. Sci. Lett.,* 181(3):429–441. **doi:10.1016/S0012-821X(00)00211-9**

Constable, C., and McElhinny, M., 1985. Holocene geomagnetic secular variation records from northeastern Australian lake sediments. *Geophys. J. R. Astron. Soc.,* 81:103–120.

Creer, K., Valencio, D., Sinito, A., Tucholka, P., and Vilas, J., 1983. Geomagnetic secular variations 0–14,000 yr BP as recorded by lake sediments from Argentina. *Geophys. J. R. Astron. Soc.,* 74:199–221.

Gogorza, C.S.G., Sinito, A.M., Lirio, J.M., Nunez, H., Chaparro, M., and Vilas, J.F., 2002. Paleosecular variations 0–19,000 years recorded by sediments from Escondido Lake (Argentina). *Phys. Earth Planet. Int.,* 133(1–4):35–55. **doi:10.1016/S0031-9201(02)00086-9**

Gogorza, C.S.G., Sinito, A.M., Vilas, J.F., Creer, K.M., and Nunez, H., 2000. Geomagnetic secular variations over the last 6500 years as recorded by sediments from lakes of south Argentina. *Geophys. J. Int.,* 143:787–798. **doi:10.1046/j.1365-246X.2000.00277.x**

Kono, M., and Roberts, P.H., 2002. Recent geodynamo simulations and observations of the geomagnetic field. *Rev. Geophys.,* 40(4):1013. **doi:10.1029/2000RG000102**

Lamy, F., Kaiser, J., Ninnemann, U., Hebbeln, D., Arz, H.W., and Stoner, J., 2004. Antarctic timing of surface water changes off Chile and Patagonian ice sheet response. *Science,* 304(5679):1959–1962. **doi:10.1126/science.1097863**

Lamy, F., Rühlemann, C., Hebbeln, D., and Wefer, G., 2002. High- and low-latitude climate control on the position of the southern Peru-Chile Current during the Holocene. *Paleoceanography,* 17(2):1028. **doi:10.1029/2001PA000727**

Liddicoat, J.C., and Coe, R.S., 1979. Mono Lake geomagnetic excursion. *J. Geophys. Res.,* 84:261–271

Lund, S.P., 1993. Paleomagnetic secular variation. In *Trends in Geophysical Research.* Counc. Sci. Res. Integr., 143–155.

Lund, S.P., 1996. A comparison of Holocene paleomagnetic secular variation records from North America. *J. Geophys. Res.,* 101(B4):8007–8024. **doi:10.1029/95JB00039**

Lund, S.P., Acton, G., Clement, B., Okada, M., and Williams, T., 1998. Initial paleomagnetic results from ODP Leg 172: high resolution geomagnetic field behavior for the last 1.2 Ma. *Eos, Trans. Am. Geophys. Union,* 79:178–179.

Lund, S.P., Schwartz, M., Keigwin, L., and Johnson, T., in press. Deep-sea sediment records of the Laschamp geomagnetic field excursion (~40,000 radiocarbon years BP). *Geophys. J. Int.*

Lund, S.P., Stoner, J.S., Mix., A.C., Tiedemann, R., Blum, P., and the Leg 202 Shipboard Scientific Party, 2003. Appendix: observations on the effect of a nonmagnetic core barrel on shipboard paleomagnetic data: results from ODP Leg 202. *In* Mix, A.C., Tiedemann, R., Blum, P., et al., *Proc. ODP, Init. Repts.,* 202: College Station, TX (Ocean Drilling Program), 1–10. **doi:10.2973/odp.proc.ir.202.114.2003**

Lund, S.P., Williams, T., Acton, G., Clement, B., and Okada, M., 2001. Brunhes Chron magnetic-field excursions recovered from Leg 172 sediments. *In* Keigwin, L.D., Rio, D., Acton, G.D., and Arnold, E. (Eds.), *Proc. ODP, Sci. Results,* 172: College Station, TX (Ocean Drilling Program), 1–18. **doi:10.2973/odp.proc.sr.172.216.2001**

Merrill, R.T., McElhinny, M.W., and McFadden, P.L., 1996. *The Magnetic Field of the Earth: Paleomagnetism, the Core and the Deep Mantle:* San Diego (Academic).

Mix, A.C., Tiedemann, R., Blum, P., et al., 2003. *Proc. ODP, Init. Repts.*, 202: College Station, TX (Ocean Drilling Program). **doi:10.2973/odp.proc.ir.202.2003**

Turner, G.M., and Lillis, D.A., 1994. A paleomagnetic secular variation record from New Zealand during the past 2500 years. *Phys. Earth Planet. Int.,* 83(3-4):265–282. **doi:10.1016/0031-9201(94)90093-0**

Wicht, J., and Olson, P., 2004. A detailed study of the polarity reversal mechanism in a numerical dynamo model. *Geochem., Geophys., Geosys.,* 5:Q03H10. **doi:10.1029/2003GC000602**

Figure F1. Paleomagnetic secular variation (PSV) records for 0–30 mcd in Holes 1233A–1233E. Small dots = discrete measurements at 5-cm intervals, solid lines = seven-point running average. Cal. yr BP = calendar year before present. **A.** Inclination. I1–I28 = selected reproducible features. **B.** Declination. D1–D25 = selected reproducible features.

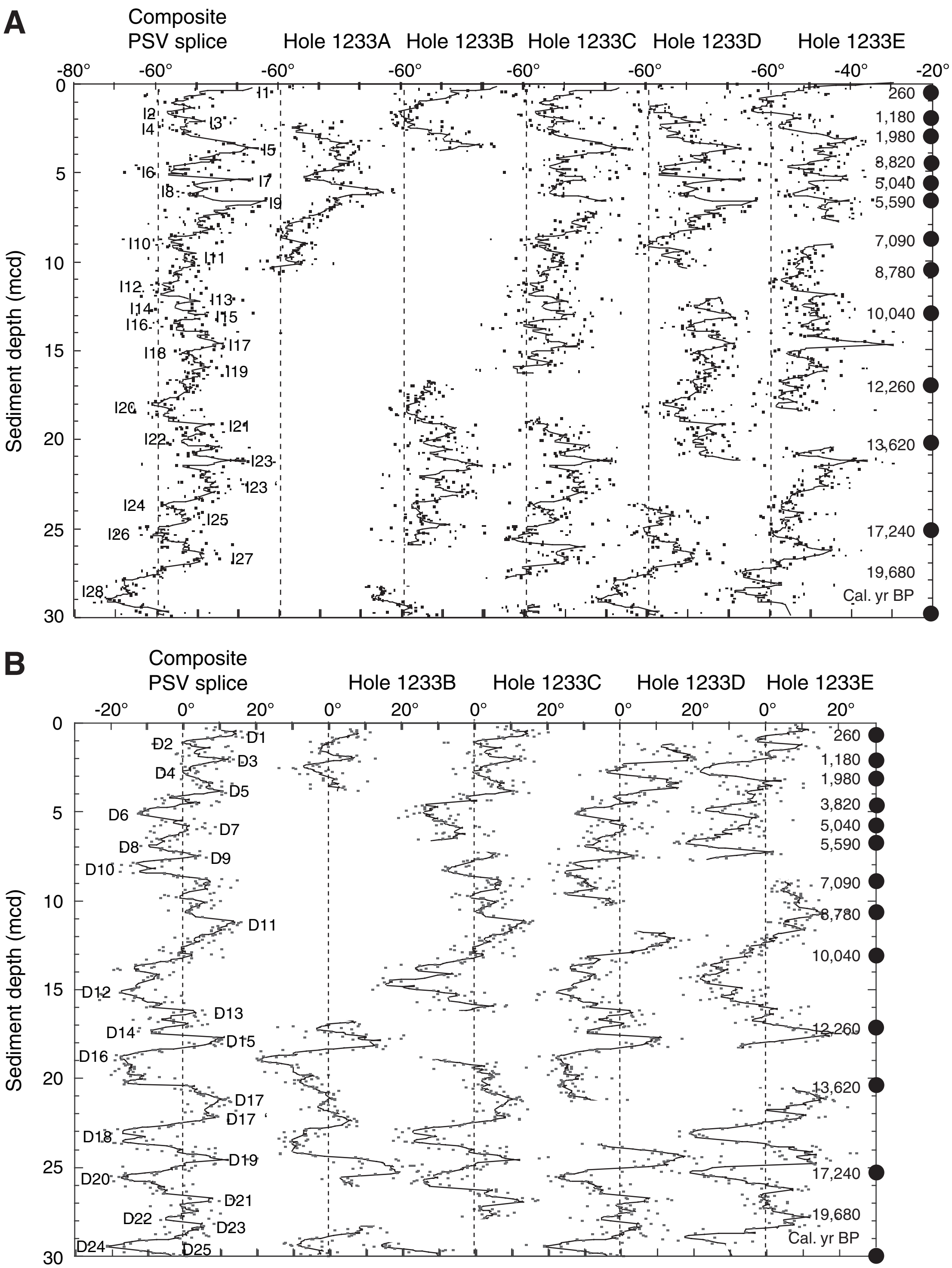


Figure F2. Paleomagnetic secular variation (PSV) records for 30–60 mcd in Holes 1233B–1233E. Small dots = discrete measurements at 5-cm intervals, solid lines = seven-point running average. Cal. yr BP = calendar year before present. **A.** Inclination. I29–I50 = selected reproducible features. Features are normally noted in at least three individual holes; features shown in parentheses are only seen in two holes. **B.** Declination. D26–D44 = selected reproducible features.

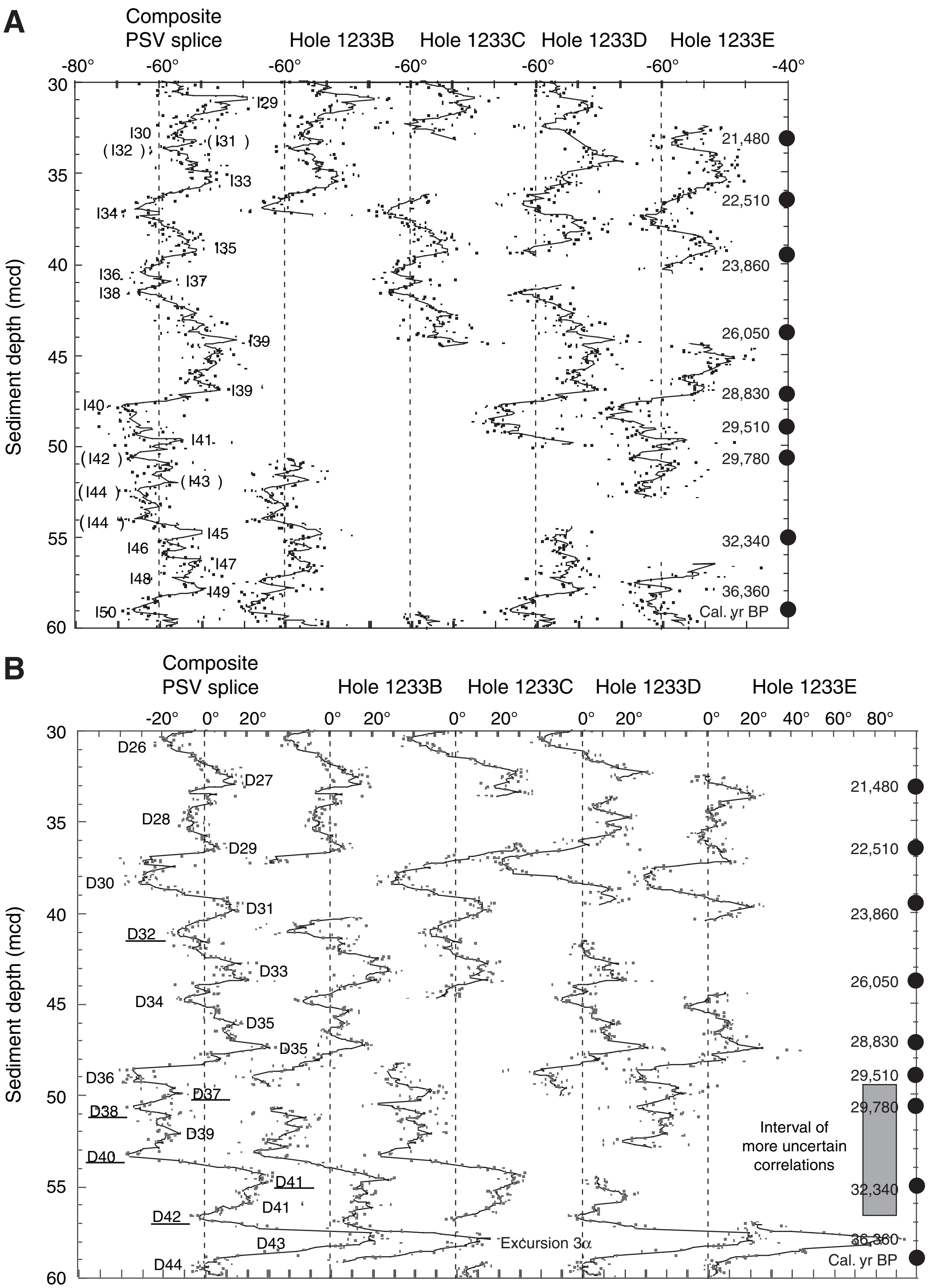


Figure F3. Paleomagnetic secular variation (PSV) records for 60–90 mcd in Holes 1233B–1233E. Small dots = discrete measurements at 5-cm intervals, solid lines = seven-point running average. Features are normally noted in at least three individual holes; features shown in parentheses are only seen in two holes. See Figure F6, p. 16, for detailed records for Excursion 3β. **A.** Inclination. I51–I78 = selected reproducible features. **B.** Declination. D45–D71 = selected reproducible features.

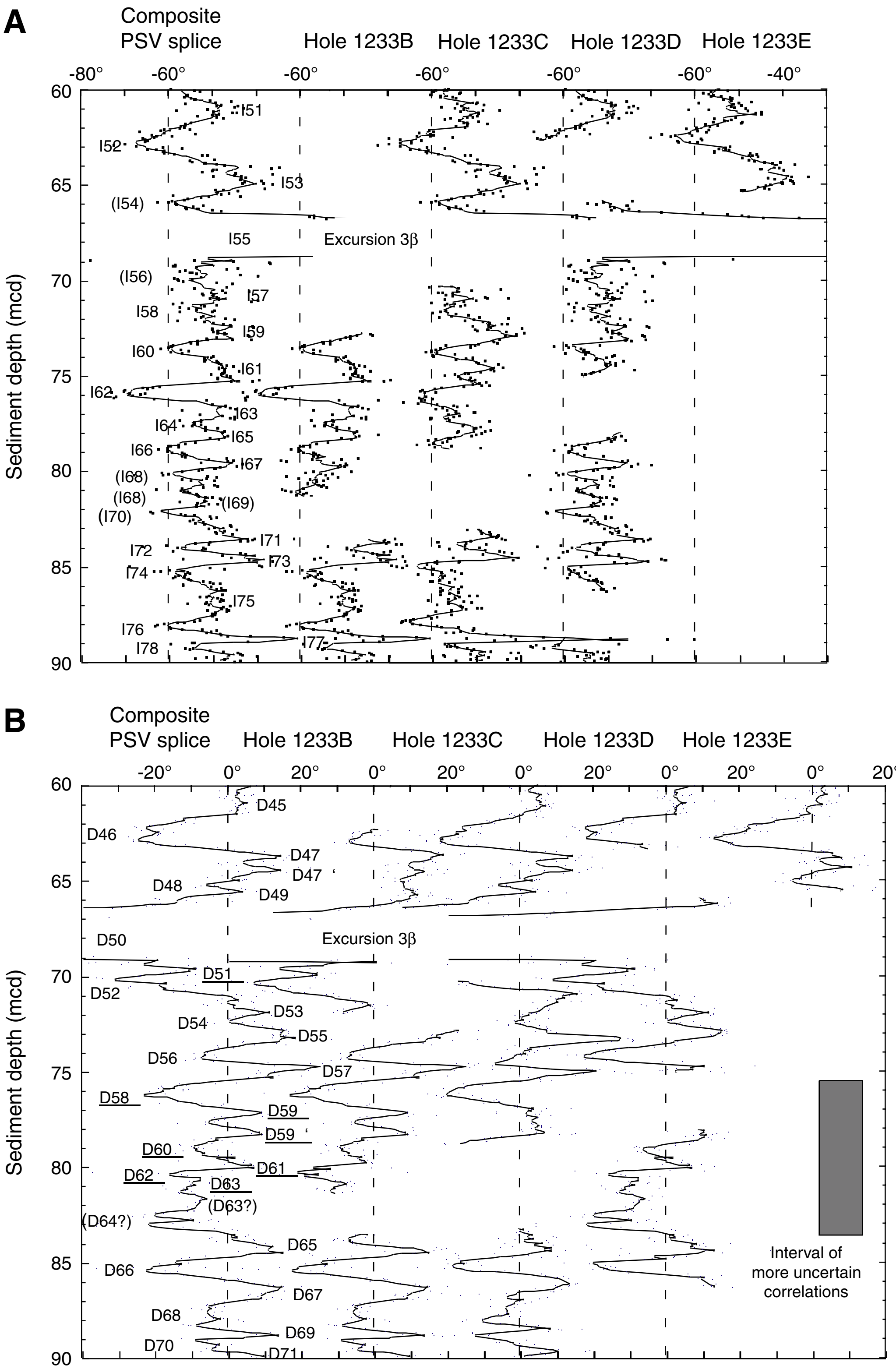


Figure F4. Paleomagnetic secular variation (PSV) records for 90–120 mcd in Holes 1233B–1233E. Small dots = discrete measurements at 5-cm intervals, solid lines = seven-point running average. Features are normally noted in at least three individual holes; features shown in parentheses are only seen in two holes. **A.** Inclination. I79–I94 = selected reproducible features. **B.** Declination. D72–D98 = selected reproducible features.

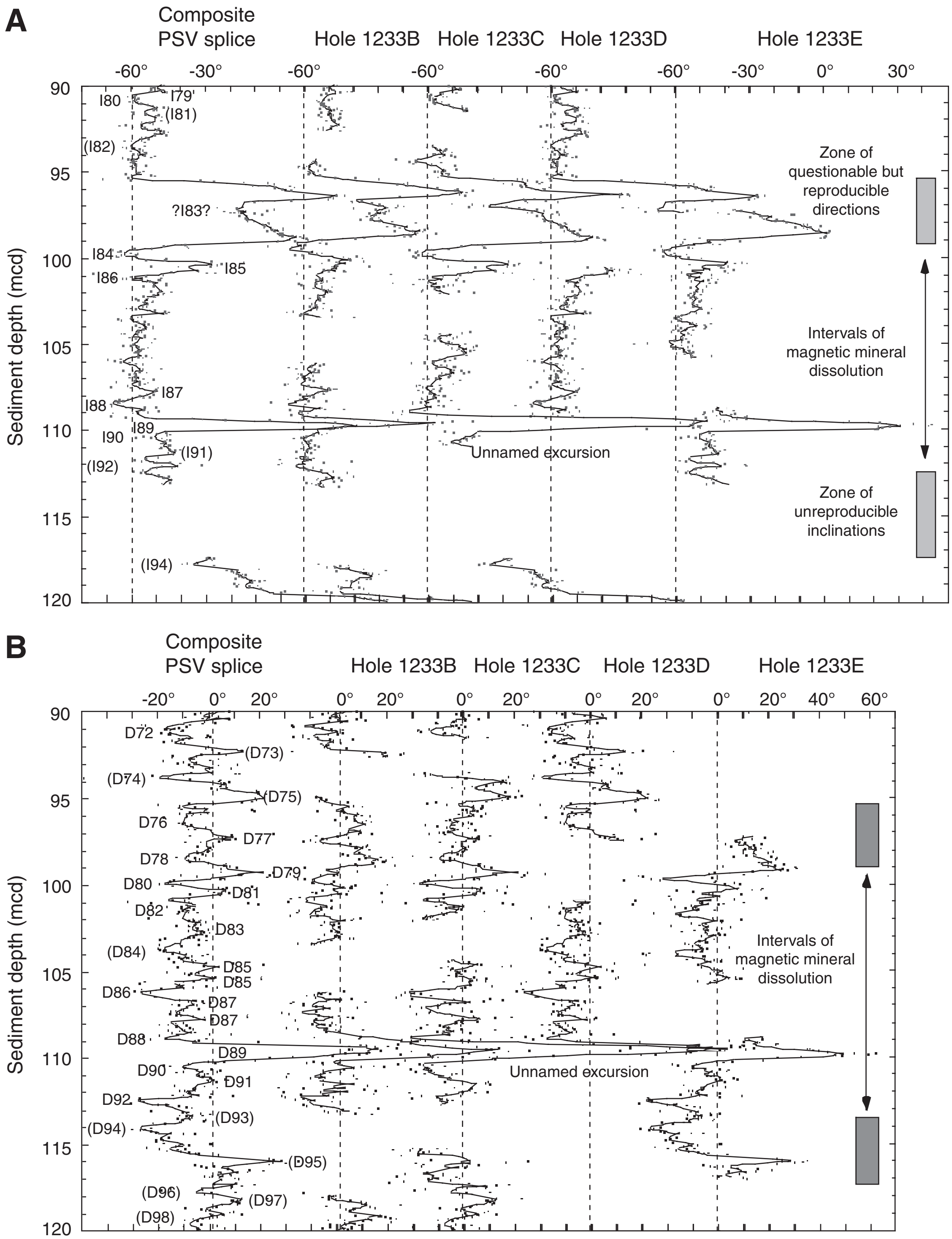


Figure F5. Paleomagnetic secular variation (PSV) records for 120–140 mcd in Holes 1233B–1233D. Small dots = discrete measurements at 5-cm intervals, solid lines = seven-point running average. Features are normally noted in at least three individual holes; features shown in parentheses are only seen in two holes. **A.** Inclination. I95–I106 = selected reproducible features. **B.** Declination. D99–D111 = selected reproducible features. ??? = questionable features, which are not reproduced in multiple holes.

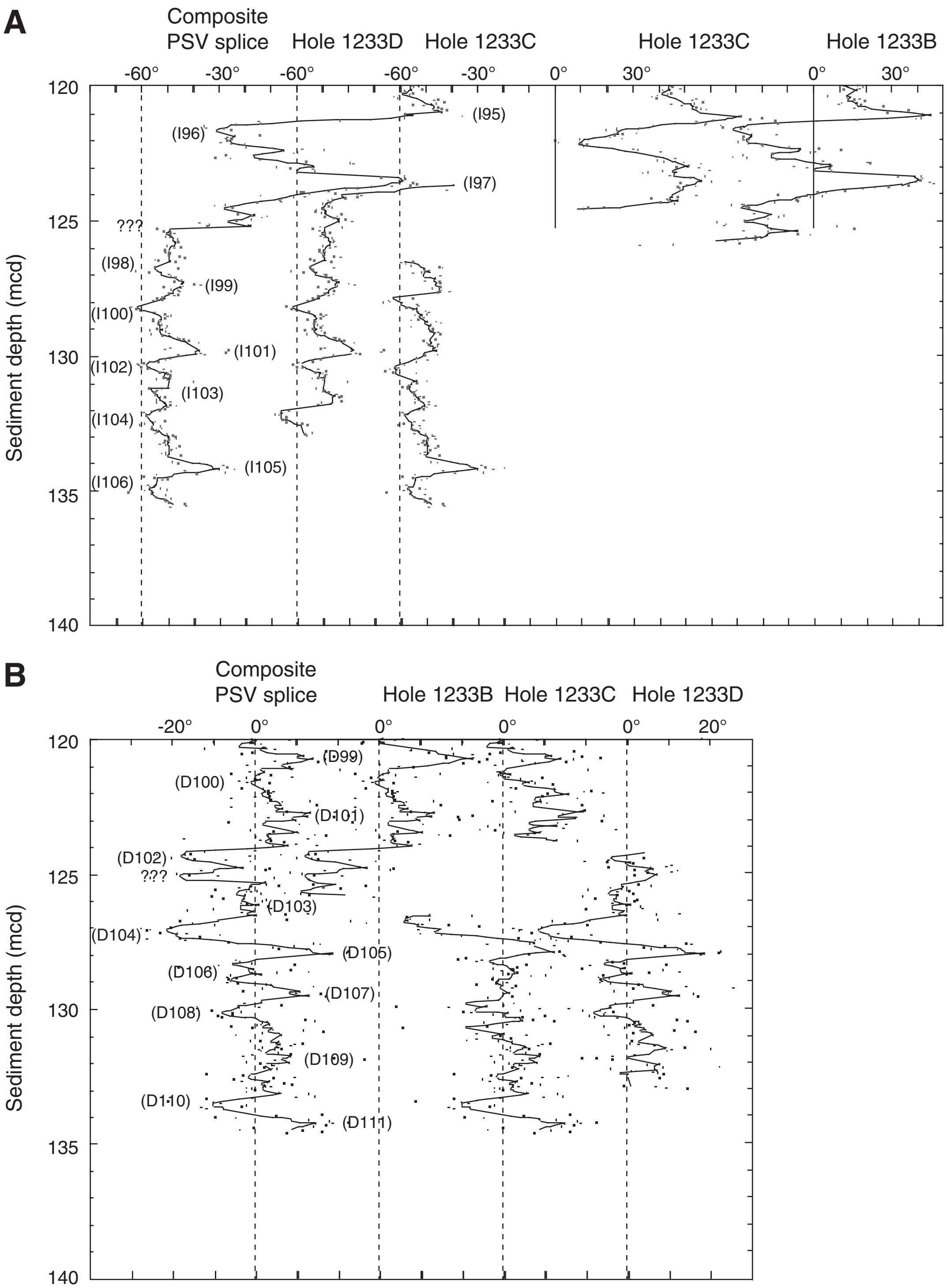


Figure F6. Detailed paleomagnetic secular variation (PSV) records for Excursion 3β at Site 1233 (see Fig. F3, p. 13). Features are normally noted in at least three individual holes; features shown in parentheses are only seen in two holes. **A.** Inclination. I53–I56 = selected reproducible features. **B.** Declination. D47–D52 = selected reproducible features.

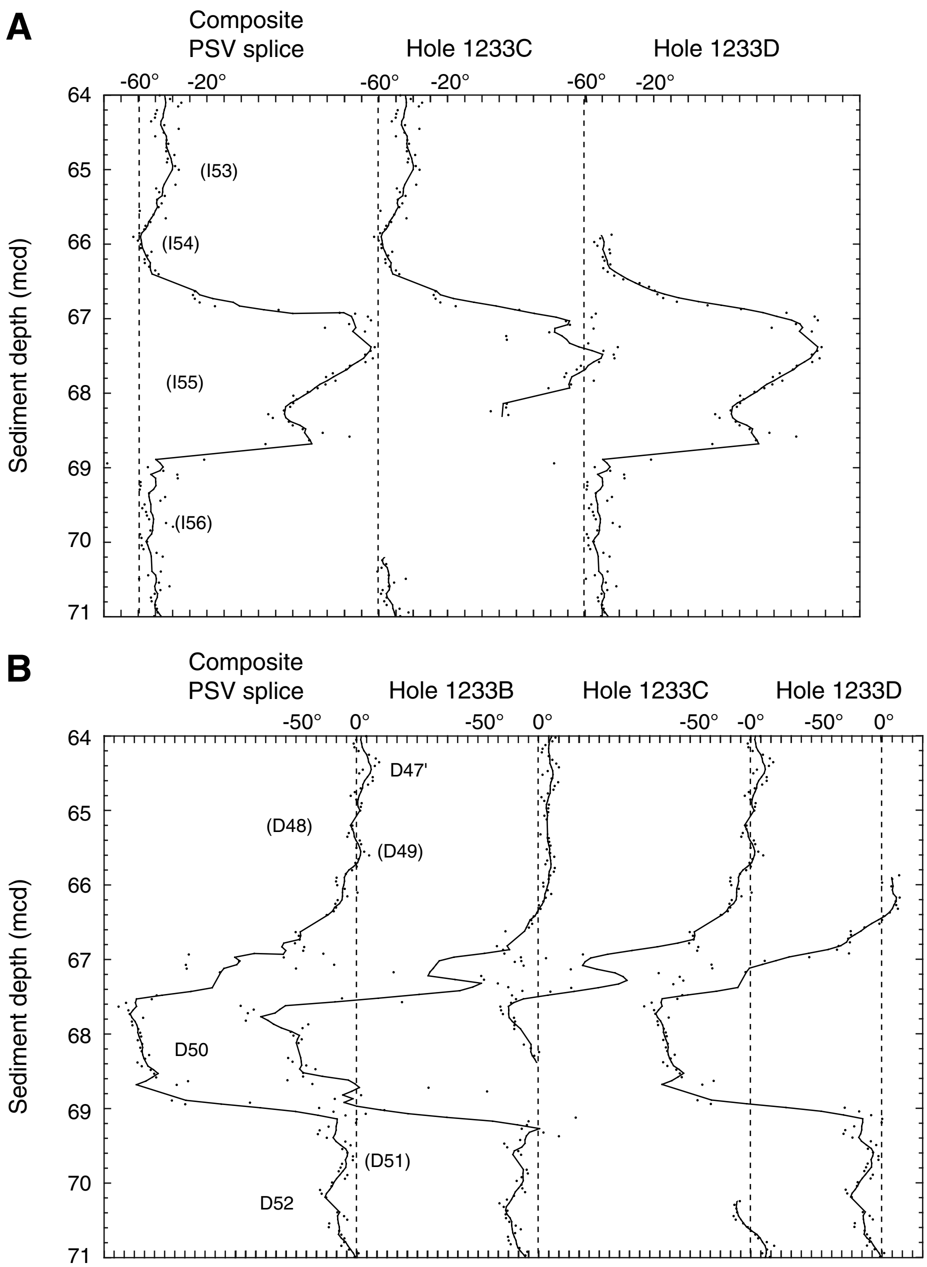


Figure F7. Paleomagnetic secular variation (PSV) records for 0–15 mcd in Holes 1234A–1234C. Small dots = discrete measurements at 5-cm intervals, solid lines = seven-point running average. **A.** Inclination. I1–I26 = selected reproducible features. Features are normally noted in at least three individual holes; features shown in parentheses are only seen in two holes. **B.** Declination. D1–D26 = selected reproducible features.

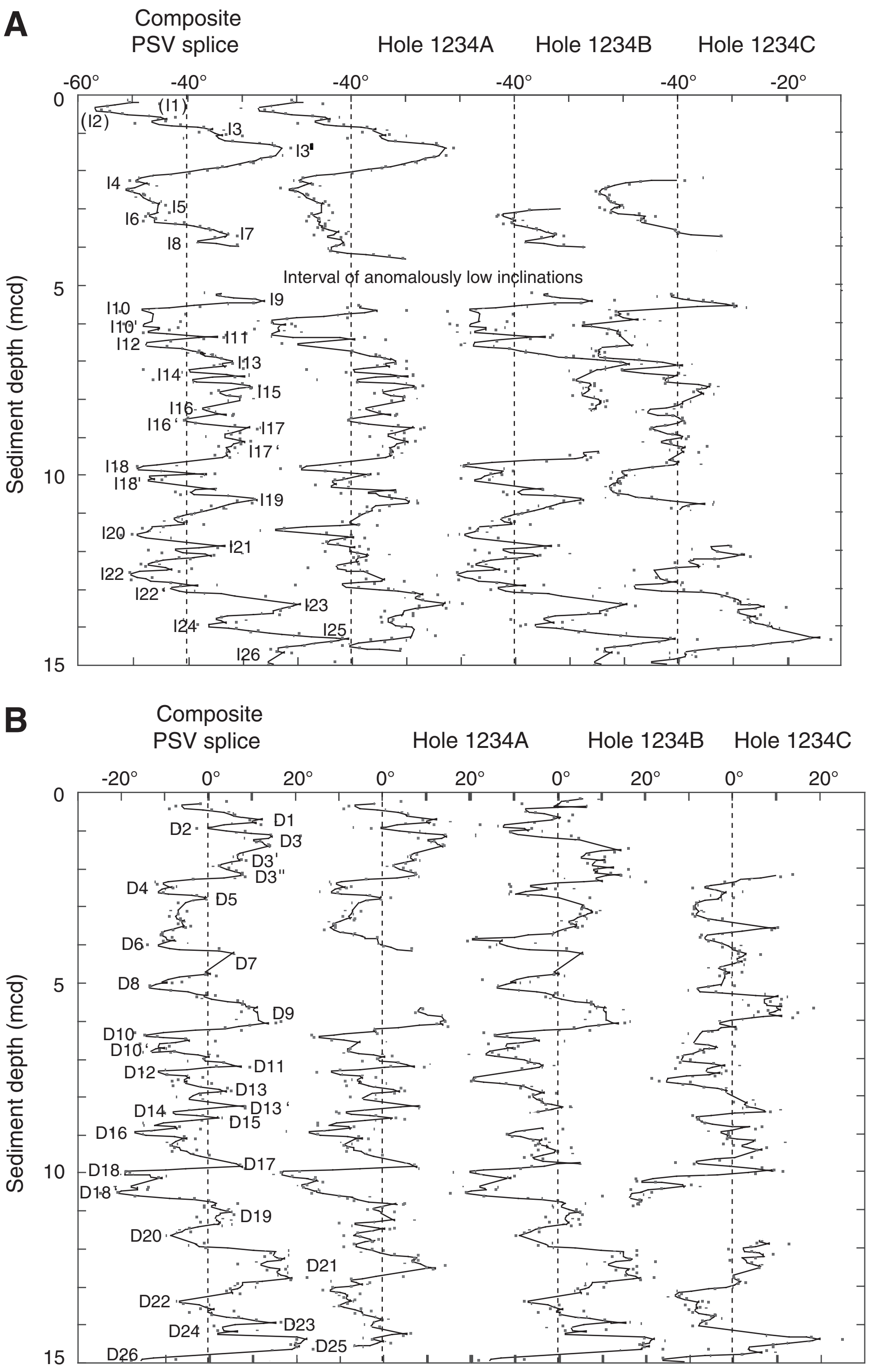
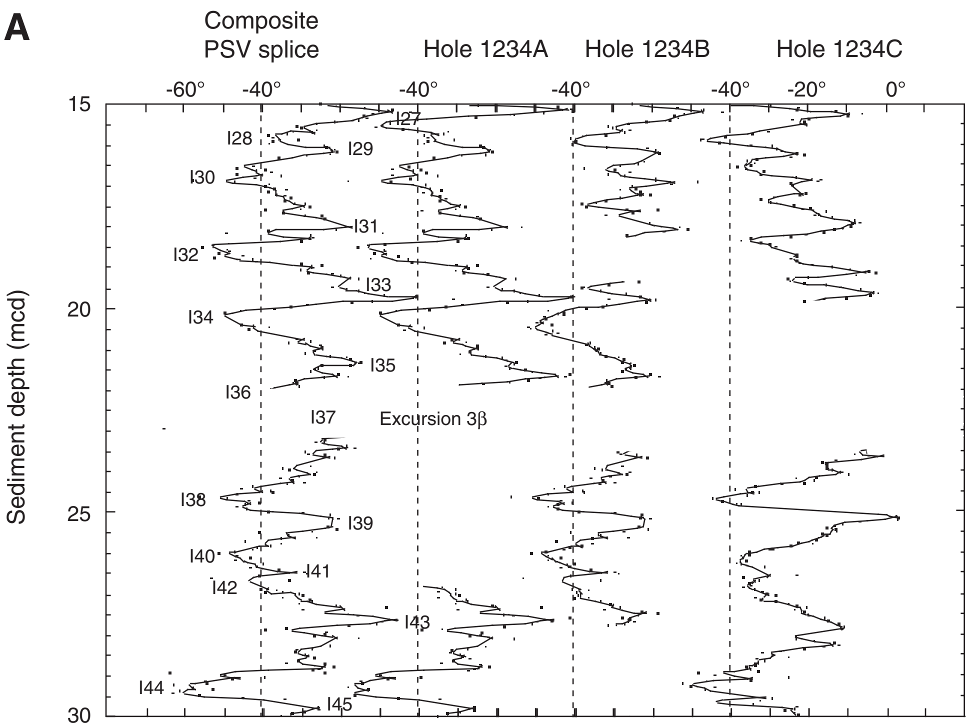


Figure F8. Paleomagnetic secular variation (PSV) records for 15–30 mcd in Holes 1234A–1234C. Small dots = discrete measurements at 5-cm intervals, solid lines = seven-point running average. See Figure F9, p. 19, for detailed records for Excursion 3β. **A.** Inclination. I27–I45 = selected reproducible features. **B.** Declination. D27–D47 = selected reproducible features.



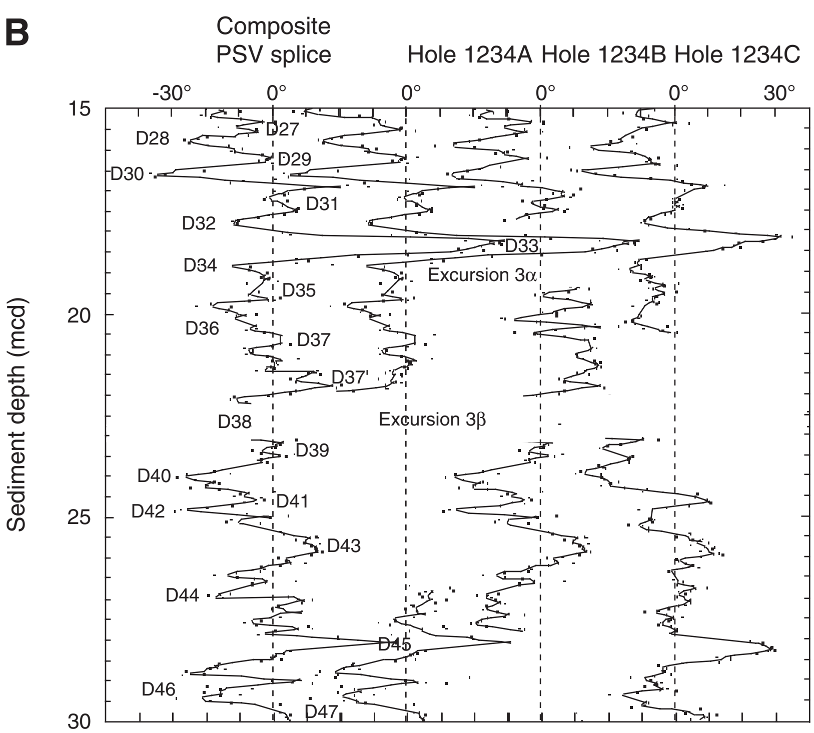
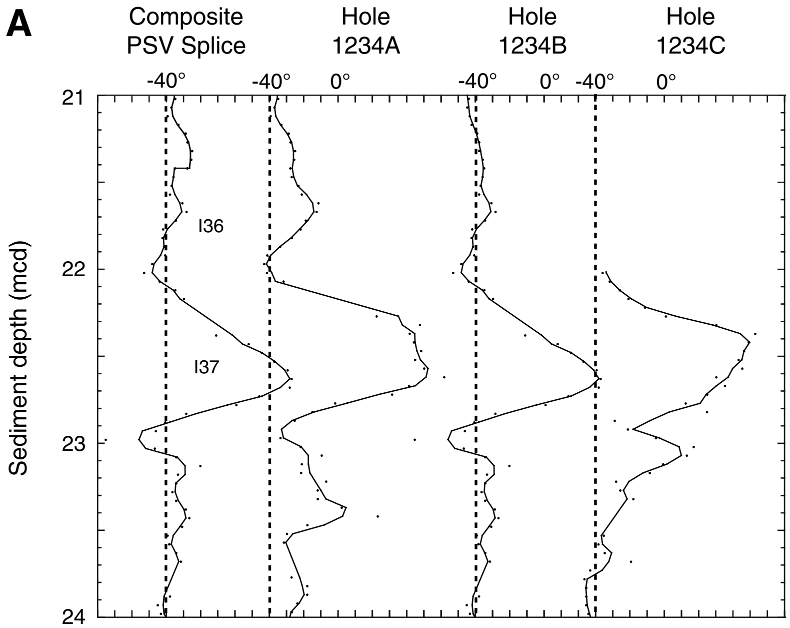


Figure F9. Detailed paleomagnetic secular variation (PSV) records for Excursion 3β at Site 1234 (see Fig. F7, p. 17). **A.** Inclination. I36 and I37 = selected reproducible features. **B.** Declination. D37–D39 = selected reproducible features.



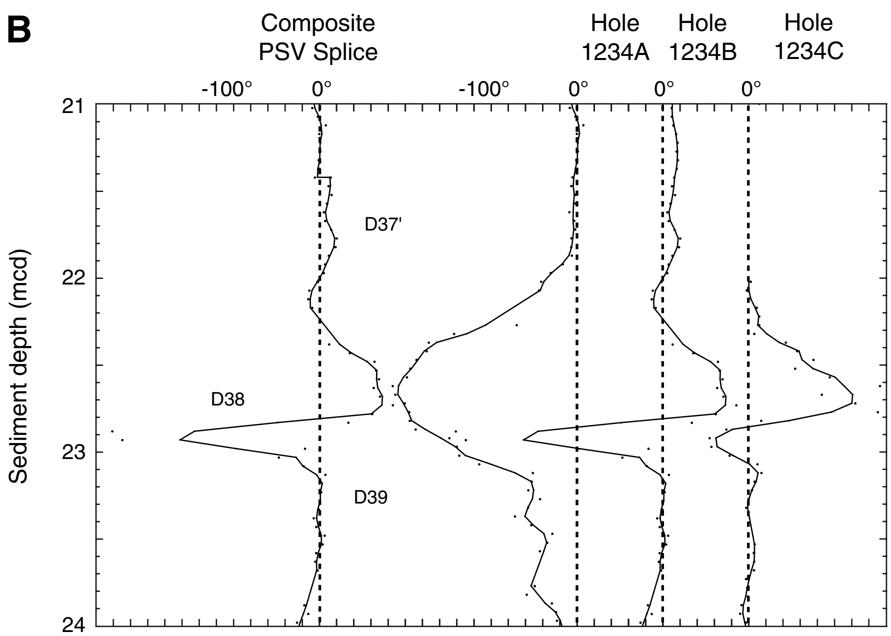


Figure F10. Depth correspondence for PSV features correlatable between Sites 1233 and 1234.

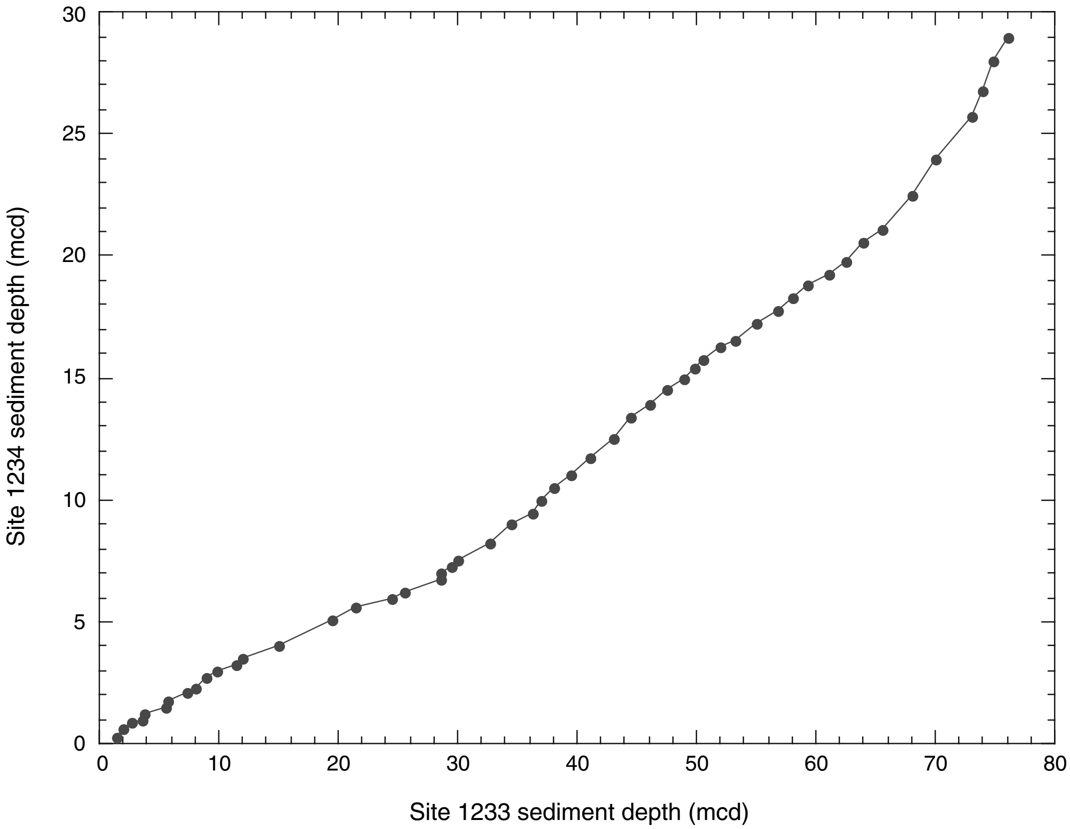


Figure F11. Time-depth plot based on 27 AMS radiocarbon dates (solid dots) from Site 1233 that were transferred to Site 1234 depths based on depth correlation curve in Figure F10, p. 20. Squares = depth interval for excursions at each site. BP = before present.

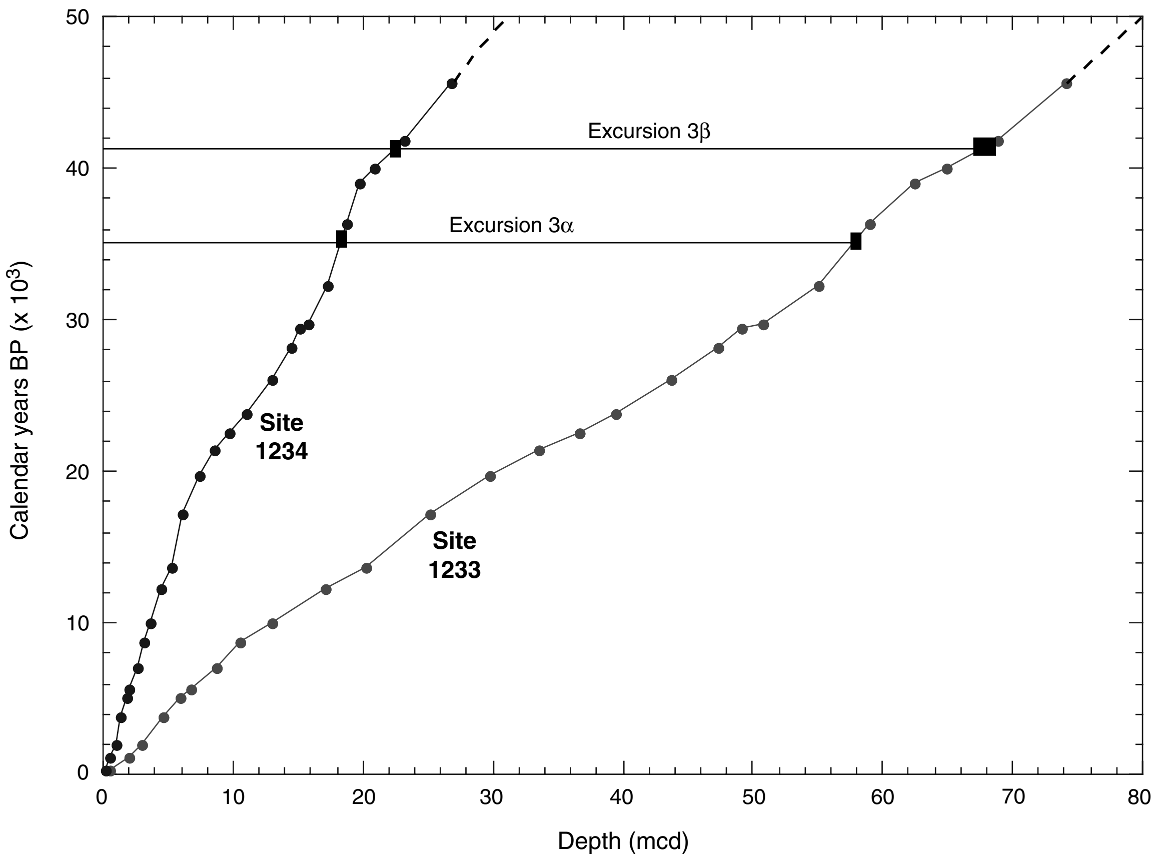


Figure F12. PSV time series from Sites 1233 and 1234 for the last 50,000 yr. Selected correlatable inclination and declination features are indicated by vertical lines. BP = before present.