1 Paleomagnetic Field Variability and Chronostratigraphy of Brunhes-Chron Deep-Sea
2 Sediments from the Bering Sea: IODP Expedition 323

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12 ABSTRACT

13 IODP Expedition 323 recovered six complete and replicate records of Brunhes-
14 Chron paleomagnetic field variability (0-780,000 years BP) in 2820 meters core depth
15 below sea floor (CSF) of deep-sea sediments. On shipboard, we made more than 220,000
16 paleomagnetic measurements on the recovered sediments. Since then, we have u-channel
17 sampled more than 300 m of Brunhes Chron sediments to corroborate our shipboard
18 measurements and improve our paleomagnetic and rock magnetic understanding of these
19 sediments. Several intervals of distinctive paleomagnetic secular variation (PSV) have
20 been identified that appear to be correlatable among Sites 1343, 1344, and 1345. One
21 magnetic field excursion is recorded in sediments of Sites 1339, 1343, 1344, and 1345.
22 We identify this to be Excursion 7a/Iceland Basin Event (192,000 years BP), which is
23 also seen in the high-latitude North Atlantic Ocean (Channell et al., 1997). We have

verified in u-channels the placement of the Brunhes/Matuyama boundary at Sites 1341 and 1343. Finally, we have developed a medium-quality relative paleointensity record for these sediments that is correlatable among the sites, even though it is still biased by large-amplitude environmental variability. On the basis of these observations we have built a magnetic chronostratigraphy of Expedition 323 sediments suitable for regional correlation and dating over the last 1 million years, and compared this with oxygen-isotope chronostratigraphy from Sites U1339 and U1345.

1. Introduction

Integrated Ocean Drilling Program (IODP) Expedition 323 (Takahashi et al., 2011) recovered 5741 meters of Quaternary and Pliocene sediments from seven sites (Figure 1) in the Bering Sea (53.7°N-60.1°N). Note that CSF is meters core depth below seafloor and is generally equivalent to the previous Ocean Drilling Program (ODP) term meters below seafloor (MBSF); meters CCSF is meters core composite depth below seafloor and is generally equivalent to the previous ODP term meters composite depth (MCD). Four of the sites (U1339, U1343, U1344, and U1345) are located along the northern Bering Sea margin and are termed Bering Slope sites (1008-3184 m water depth); three of the sites (U1340, U1341, and U1342) are located in the south central Bering Sea along the deep-sea Bowers Ridge and are termed the Bowers Ridge sites (830-2150 m water depth). All seven sites share a depositional history that relates to ocean circulation in the Bering Sea (e.g., Takahashi, 2005) and its connections to more large-scale Northern Pacific circulation, which are driven by climate changes (e.g., Tanaka and Takahashi, 2005).

2820 meters CSF of these Bering Sea sediments are Brunhes Chron in age (0-780,000 years BP) with 6 complete records of Brunhes Chron paleomagnetic field variability: Site U1339 (23.1 cm/kyr average sediment accumulation rate), U1340 (16.0 cm/kyr), U1341 (10.6 cm/kyr), U1342 (3.2 cm/kyr), U1343 (23.7 cm/kyr), U1344 (34.6 cm/kyr). Site U1345 recovered only the last half of the Brunhes Chron at 23.0 cm/kyr. This sequence of sediments represents the highest-resolution composite record of potential Brunhes Chron geomagnetic field behavior ever recovered in the World. These records are located geographically between two high-latitude flux-lobes (Bloxxham and Gubbins, 1985; Gubbins and Bloxxham, 1987) situated at the core/mantle boundary, one below North America and the second below East Asia (Figure 1). Figure 1 also shows the locations of other complete Brunhes Chron sequences of paleomagnetic field variability previously recovered (Jansen et al., 1996; Backman et al., 2006; Channell et al., 2006;). All of those sediment records have average sediment accumulation rates less than 18.0 cm/kyr (Table 1).

More than 220,000 paleomagnetic measurements were made on the IODP Expedition 323 cores during the cruise (Takahashi et al., 2011) and more than 300 meters of the Brunhes Chron sediments have been more recently u-channelled and selectively demagnetized to corroborate the shipboard measurements and further assess the paleomagnetic and rock magnetic character of the sediments. This paper summarizes our shipboard paleomagnetic measurements, further new analysis of our shipboard measurements, and new u-channel paleomagnetic studies, which corroborate shipboard measurements. This paper describes the overall paleomagnetic field variability recovered

from these sediments during the Brunhes Chron and develops a magnetic chronostratigraphy that can be used to correlate the sediments among the seven sites

2. Shipboard Paleomagnetic Measurements

Shipboard paleomagnetic measurements commonly measured the initial natural remanence (NRM) of the archive-half-round core sections in at least one hole at each site. The NRMs were then step-wise demagnetized in alternating magnetic fields at 10 mT, 15 mT, and 20 mT to assess the relative strength and ease of removal of a viscous remanence (VRM), which is ubiquitously present in IODP cores (e.g., Lund et al., 2003). Shipboard measurements between 10 mT to 20 mT almost always had good reproducible directions and appeared to effectively remove the VRM. Other holes were commonly only demagnetized at 20 mT. The shipboard paleomagnetic secular variation records from all 7 sites are summarized and plotted in Takahashi et al. (2011).

Several stratigraphic parameters, including magnetic susceptibility, have been used to correlate holes at each site and develop a modified depth scale (meters CCSF) that provides a correlation resolution among holes of ~10 cm (Takahashi et al., 2011). This modified depth scale has been used to correlate the 20 mT demagnetized paleomagnetic directions among all holes at each site and build a composite paleomagnetic secular variation record for each site (Takahashi et al., 2011) for the Brunhes Chron (0-780,000 years BP). The paleomagnetic directions in individual holes had occasional anomalies, which we associate with ice-rafted debris (IRD) or localized sediment disturbances that were not correlatable between holes at each site. These directions were removed from the paleomagnetic records. The remaining directional

variability in each hole (>95% of each record) was correlatable between holes (see examples below). The cores were oriented to North during the coring process, but unresolved errors limited the accuracy of core reorientation to $\sim\pm 20^\circ$ at best. For our analysis, we preferred to reorient each core (~9.5 m in length, 38,000 to 90,000 years in duration) by rotating each core's mean declination to 0° declination. This methodology permitted us to develop a composite paleomagnetic record of Brunhes Chron paleomagnetic field variability from each site. The only limitation is that paleomagnetic declination variability longer in duration than ~50,000 years will be subdued or lost.

3. New Paleomagnetic Measurements

3.1. Paleomagnetic Secular Variation

We have now carried out new paleomagnetic measurements on 300 meters of selected cores, which were sampled using u-channels. U-channels remove a column of sediment, 2×2 cm in cross section, from the split face of a core. These u-channels should provide the most undisturbed sediment for paleomagnetic measurements. U-channels are taken from the same cores that were used for the shipboard paleomagnetic studies. We have carried out detailed paleomagnetic measurements on these cores to compare with the shipboard measurements and assess the extent to which the shipboard measurements are a reasonably faithful record of paleomagnetic field variability.

All u-channels were initially measured at 20 mT alternating field (AF) demagnetization and then step-wise AF demagnetized at 5-10 mT steps up to 100 mT. Figure 2 shows Zijderveld demagnetization plots for four selected u-channel horizons to document the pattern of NRM demagnetization in the Bering Sea sediments. Two

Zijderveld diagrams (Figures 2a, d) are from surficial (Holocene) sediments; the other two Zijderveld diagrams (Figures 2b, c) are from mid-Brunhes Chron (~400,000 year old) sediments. Two of the sediment horizons (Figures 2a, c) are associated with low values of magnetic susceptibility and NRM intensity and two (Figures 2b, d) are associated with high values. All show a simple pattern of AF demagnetization toward the origin (indicated by dashed lines in Figure 2) between 20-80 mT.

Figure 3 shows a comparison of shipboard and u-channel measurements of inclination and declination, demagnetized at 20 mT, for two sediment intervals from two different sites. The results are not significantly different. Both data sets show the same overall pattern of directional variability. Statistical analysis shows that the scalar inclination and declination mean values and their standard deviations are not significantly different. The Hole 1341B (Figure 3, top) vector mean directions are $I=57.4^\circ$, $D=275.1^\circ$, $\alpha_{95}=2.5^\circ$ for shipboard data and $I=56.1^\circ$, $D=272.5^\circ$, $\alpha_{95}=2.3^\circ$ for u-channel data. The Hole 1344A (Figure 3, bottom) vector mean directions are $I=77.4^\circ$, $D=173.1^\circ$, $\alpha_{95}=1.5^\circ$ for shipboard data and $I=75.6^\circ$, $D=175.5^\circ$, $\alpha_{95}=1.3^\circ$ for u-channel data. These results are typical for all of our u-channel measurements.

The u-channel inclinations and declinations do not change significantly from their 20 mT values upon further demagnetization to at least 80 mT. This means that the paleomagnetic directions are decaying toward the origin during AF demagnetization. These results corroborate our shipboard estimate that any viscous remanence (VRM) was largely demagnetized by 20 mT so that the 20 mT or higher demagnetization NRM values should reflect the real paleomagnetic field variability recorded in the sediments. This also indicates that our shipboard measurements can be used for analysis of

paleomagnetic field variability. This is important because we cannot possibly u-channel sample all 2800 meters CSF of Brunhes-aged sediments to assess Brunhes paleomagnetic field variability.

3.2. Magnetic Field Excursions

Previous studies have noted that magnetic field excursions may be a common element of Brunhes geomagnetic field behavior (e.g., Lund et al., 2006; Laj and Channell, 2007). No significant evidence for excursions was observed from shipboard magnetic measurements during the expedition (Takahashi et al., 2011). Excursions are short-duration anomalous features of the geomagnetic field. We can only define their potential existence in our cores by replicating anomalous paleomagnetic results from multiple holes at each site and also replicating anomalous results between sites, given the correlations and dating that we summarize here. This is a very large task that is still in progress and was largely beyond our ability to carefully evaluate in the limited time aboard ship while we were also making continuous regular paleomagnetic measurements. Subsequent ongoing analysis of our shipboard data and corroboration of data quality with our selected u-channel studies has now identified one clear excursion, which we interpret to be excursion 7a/Iceland Basin Event (~192,000 years BP; Channell et al., 1997; Robert et al., 1997; Lund et al., 2001, 2006; Knudsen et al, 2007, 2008). We can replicate this excursion record at 4 sites (U1339, U1340, U1343, and U1344; Table 2). Sites U1343 and U1344 have high-resolution records of the excursion (Figure 4); Sites U1339 and U1340 have reproducible anomalous directions that we correlate with U1343 and U1344, but they are lower sediment accumulation sites and do not have as high a

resolution in the pattern of excursions in the pattern of excursions field behavior. We also see some evidence for other excursions at sites U1343, U1344, and U1345, but more work is needed to correlate the excursions field variability among all the holes at all the sites and assess whether the excursions can be replicated there. The placements of Excursion 7a and three older potential excursions are summarized in Table 2. The number of Brunhes-aged excursions, which we have identified at our high-latitude sites, so far, is small (<10) compared to paleomagnetic results at lower latitudes (15 or more; e.g., Lund et al., 2001, 2007). This small number of high-latitude excursions is consistent with the results of Channell and Raymo (2003) for similar high-latitude sites in the North Atlantic Ocean.

Two records of excursion 7a from Holes U1343A and U1344E are shown in Figure 4. These data come from shipboard measurements (20 mT AF demagnetization), but the detailed variability in Hole U1344E has been replicated in u-channel measurements (Mortazavi et al., 2011). The detailed excursions field behavior is replicated in Holes U1343A and U1343C and Holes U1344 A and U1344E. Lower resolution records of this excursion are also noted at Sites U1339 and U1340. The pattern of field behavior is distinctive in that the directions go through a complete field reversal, but the intervals of large inclination and declination changes (indicated by dashed lines in Figure 4) do not occur at the same time (out of phase). Other excursions (Blake Event, Lund et al., 2001; Laschamp Excursion in the Southern Hemisphere, Lund et al., 2006) have inclination and declination swings from one polarity to the other at the same time (in phase).

3.3. Brunhes/Matuyama Polarity Transition

The Brunhes/Matuyama polarity transition was clearly identified at six sites based on shipboard measurements. We have now u-channel sampled four of the transition intervals to assess the detailed field behavior during the reversal. Our measurements of the u-channels clearly indicate that the placement of the Brunhes/Matuyama boundary based on shipboard measurements was correct. Figure 5 shows shipboard measurements (open symbols, 20 mT) and u-channel measurements (solid symbols, 20 mT) of the Brunhes/Matuyama boundary at two different sites – U1341A and U1343C. At both sites, the polarity transition is sharp, lasting perhaps less than 2000 years. Future u-channel work is needed to more carefully assess the character of the transition, but these measurements indicate that the stratigraphic placement of the Brunhes/Matuyama boundary is clear-cut and can be used to help build our magnetic chronostratigraphic framework. The placements of the Brunhes/Matuyama boundary for each site are summarized in Table 2. Directional variability before the Brunhes/Matuyama boundary in Stage 20 (or early Stage 19) (Figure 5 top and bottom) could be a Brunhes precursor excursion (e.g., Channell et al., 2004); the U1343C directional variability in early Stage 21 (Figure 5 bottom) could be the Kamikatsura Excursion (Laj and Channell, 2007).

3.4. Rock Magnetic Studies

The sediments have a generally strong magnetic remanence that undergoes order-of-magnitude oscillations in intensity at a ~5-20 meter scale. Magnetic susceptibility (χ) undergoes a similar pattern of intensity oscillation (Figure 6). We interpret this to be largely controlled by glacial-interglacial/interstadial changes in Bering Sea sedimentation. We have identified 29 Brunhes-aged peaks in magnetic susceptibility that

appear to be correlatable among all the sites (Takahashi et al., 2011). The stratigraphic locations of chi peaks for each site are summarized in Table 2. Our initial estimate (Takahashi et al., 2011) was that these correlatable features could be used as a relative magnetic chronostratigraphic framework for the seven Bering Sea sites.

It is typical in IODP cored sediments to have a magnetic overprint associated with drilling operations (e.g., Lund et al., 2003). We evaluated that overprint during shipboard measurements (Takahashi et al., 2011) and concluded that 20 mT AF demagnetization of the NRM could effectively remove that soft ‘viscous’ remanence. Our detailed rock magnetic analysis of selected u-channels suggests that the soft ‘viscous’ remanence is carried by the coarsest detrital magnetic grains (magnetite/titanomagnetite) and perhaps, on occasion, some authigenic minerals that have a very soft remanence. Demagnetization of the u-channels shows that the NRM carrying the main paleomagnetic signal (a simple vector direction that smoothly demagnetizes toward the origin) is demagnetized between 20 and 80 mT (Figure 2) with almost no NRM left after 100 mT. We attribute the NRM directions, which were demagnetized between 20 and 80 mT, to be a detrital magnetite/titanomagnetite contribution and thus assign it to a depositional remanence suitable for more detailed paleomagnetic study. The detrital magnetite/titanomagnetite has a slightly coarser grain-size distribution (most NRM loss between 20 and 60 mT) in the high-intensity sediments and a relatively finer-grained distribution (most NRM loss between 40 and 80 mT) in the lower-intensity sediments. We do not see any significant evidence for a bias or alteration in the NRM above 20 mT (our interval of study) that might be associated with diagenetic or environmental alterations.

3.5. Relative Paleointensity Estimation

Relative paleointensity has been an effective magnetic chronostratigraphic tool for correlation and dating of deep-sea sediments (e.g., Channell and Raymo, 2003; Stoner et al., 2003, Valet et al., 2005; Channell et al., 2009). During IODP Expedition 323, we used the ratio of NRM demagnetized at 20 mT divided by magnetic susceptibility (NRM20/Chi) as an initial estimate of paleomagnetic field intensity variability (Takahashi et al., 2011). This ratio works well when there is less than order-of-magnitude variation in NRM and chi and only minor variations in grain size of the magnetic fraction. However, it was apparent from shipboard measurements that the large rock magnetic (chi) intensity changes will mask true paleointensity variability to some extent.

Even so, our subsequent analysis indicates that the NRM20/Chi variations are correlatable among all the sites of Expedition 323 (as estimated by Takahashi et al. (2011)). The strong degree of similarity between the NRM20/Chi variability and magnetic susceptibility variability alone at each hole (Figure 6) indicates a significant environmental influence. Therefore, we would not characterize our normalized remanence records as dominantly reflecting variations in the geomagnetic field. Chi and NRM20/chi are not, however, identical and both do show significant differences between them that are correlatable among the Sites. We have identified 12 NRM20/Chi peaks (Figure 6, Table 2) that are distinctive from the chi peaks; we think these NRM20/Chi variations may reflect, to some extent, relative paleointensity changes that could provide some paleomagnetic correlation applicability. As such we consider the NRM20/Chi normalized remanence as useful for local correlation, but require additional study before any geomagnetic information on past intensity can be reliably obtained. Our NRM20/Chi

correlations among the seven sites are consistent with the magnetic susceptibility correlations (Table 2).

4. Development of a Magnetic Chronostratigraphy

The paleomagnetic field features all provide a consistent means of correlating the seven sites within the Brunhes Chron. Excursions, the Brunhes/Matuyama boundary, and relative paleointensity all correlate among the seven sites in the same consistent manner. This is to be expected in that all of these are chronostratigraphic features, which should be synchronous over this region. The rock magnetic variability (chi) also correlates among the seven sites in the same pattern as the paleomagnetic features (Takahashi et al., 2011). This is expected if chi reflects regional-scale environmental variability that is synchronous. All of these correlation features are summarized in Table 2. The ages of the known paleomagnetic features (excursions, as summarized in Lund et al. (2006), and B/M boundary) are listed in Table 2, as well. Figure 7 shows the depth scale of all sites (Table 2) relative to Site U1344 (the site with the highest average sediment accumulation rate) using these correlations.

Table 2 also shows the stratigraphic position of selected oxygen isotope stage boundaries for Sites U1339 and U1345 (Cook et al., this issue), which are dated in Table 2 using the Lisiecki and Raymo (2005) time scale (see also Cook et al, this issue). The oxygen-isotope ages of the stage boundaries are consistent with the ages of our independent magnetic chronostratigraphic features. Figure 7 also shows the estimated placement of the oxygen isotope stage boundaries at all seven sites based on our magnetic chronostratigraphy. The oxygen isotope chronostratigraphy provides time-stratigraphic

corroboration of our magnetic chronostratigraphic framework and a means to correlate the Site 1339 and Site 1345 oxygen isotope chronostratigraphies to the other five sites. All of these features provide a consistent chronostratigraphic framework for all of the IODP Expedition 323 sites.

5. Paleomagnetic Field Directional Variability

We have begun to analyze the space/time character of paleomagnetic secular variation (PSV) using the individual-hole Brunhes PSV records from Sites U1339, U1340, U1341, U1343, U1344, and U1345. We have carried out directional PSV correlations among all holes at individual sites in selected time intervals. We have also carried out similar correlations among all sites. Our overall sense is that PSV correlations among holes at a site are routinely possible and correlations among sites are possible when PSV features are distinctive in shape or amplitude. The complication is that PSV is often ‘bland’ in the sense of having similar frequency content and amplitude for intervals $>10^4$ years in duration. Also, the PSV detail is best at Site U1344 with the highest sediment accumulation rate and PSV details diminish notably with lower sediment accumulation rates. Both of these factors limit the extent to which we can exactly correlate individual peaks/troughs in PSV inclination or declination among all of the sites.

Figure 8 shows the directional PSV at Holes U1344A, U1344D, and U1344E in a 10 m interval (~30,000 years) during Stage 9 (~300,000-330,000 years BP). These are the three holes that have the longest and, thus, highest resolution records of Brunhes PSV from IODP Expedition 323. The data gaps in Holes U1344D and E are intervals between

cores. One overall goal of IODP drilling is to carefully offset cores to ensure a complete composite section from each site (e.g., Takahashi et al., 2011). The PSV data clearly indicate that goal was met in this interval. We have identified 21 inclination features and 17 declination features in this interval (Figure 8). These features are present in all three holes (excepting gap intervals) with no evidence for features that are not correlatable among the three holes.

The inclination and declination both have a strong cyclicity with an average interval of ~2500-3000 years. That is consistent with Holocene PSV noted at many locations around the World (e.g., Lund, 2007). The amplitude pattern of the PSV is replicated well among all the U1344 holes. There are two distinctive westerly swings in declination (features 7 and 9 in Figure 8) that occur at times of highest inclinations (features 12 and 14 in Figure 8). The younger declination swing is about -80° and the older declination swing is about -120° . The virtual geomagnetic poles associated with these swings have latitudes greater than 50° , so these are not geomagnetic field excursions. Nevertheless, these features are distinctive and anomalous compared to 'normal' PSV. There are westerly or easterly declinations associated with high inclinations throughout the Brunhes Chron. They could be associated with times of one high-latitude flux lobe being dominant and close to the Bering Sea, westerly declinations with the East Asia flux lobe and easterly declinations with the North American flux lobe. It is not possible to assess if this pattern is associated with static flux lobes alternating in intensity dominance or if it represents motion of one or another flux lobe.

Figure 9A shows the distribution of PSV directions for Hole U1344A. The data have an approximately Fisherian distribution centered on the data mean. The Hole 1344A

inclinations are plotted versus their estimated relative paleointensity (NRM20 mT/chi) in Figure 9B. This proxy for relative paleointensity is almost certainly biased by environmental factors, but the inclination/paleointensity distribution is very similar to distributions previously noted for Quaternary deep-sea sediments of the North Atlantic Ocean. The inclinations hover around the overall data mean for intensities greater than ~20% maximum value. Anomalously low inclinations are commonly associated with only the lowest intensities. Most of the values are associated with magnetic field excursion 7a. The dispersion of inclinations diminishes as intensities raise with the highest intensity inclination values hovering around axial-dipole expectation (solid line in Figure 9B). This pattern is consistent with the theory (Cowlings Theorum; Merrill et al., 1998) that the geomagnetic field becomes most axial-dipolar at times of highest intensity, becomes more non-dipolar (variable) with decreasing intensity, and approaches, perhaps, an ‘excursion’ state prone to magnetic field excursions at intensities less than ~20% intensity maximum.

The statistical behavior of the PSV is also consistent with previous estimates of the latitude dependence of secular variation. Two statistical parameters that are most often compared are the ΔI anomaly (average site inclination – site axial dipole inclination) and the angular dispersion of either PSV directions or their equivalent VGPs (e.g., Merrill et al., 1998; Lund, 2007). The Brunhes-average ΔI anomalies and VGP dispersions for one hole at each Bering Sea site are shown in Figure 10, compared to other global values. The ΔI anomaly values are commonly 1° to 2° higher than axial dipole expectation; a pattern that has been previously noted for such high-latitude sites (Lund, 1985). We interpret this to be caused by the nearness of the Bering Sea sites to the

East Asian and North American flux lobes and the likelihood that one or the other dominates local PSV on the long-term average. The VGP dispersion average of $\sim 17^\circ$ is consistent with global long-term averages.

6. Summary

IODP Expedition has recovered high-resolution replicate records of the entire sequence of Brunhes paleomagnetic field variability. Our rock magnetic studies indicate that the primary magnetic mineral in the sediments is detrital magnetite with a depositional NRM. The ratio of NRM demagnetized at 20 mT AF divided by magnetic susceptibility has been used to provide an initial relative paleointensity estimate for the sediments. The normalized NRMs are notably biased by environmental variability and therefore, without further study, are only useful for local correlation, though some geomagnetic information is likely present. Correlation of PSV between holes at each site and between sites documents that a reproducible record of PSV is recorded at least in specific intervals. The overall character of the PSV is consistent with other records of Brunhes paleomagnetic field behavior. There is evidence for at least one magnetic field excursion in these sediments, with the possibility of two or three others based on future work. This is fewer excursions than have been noted elsewhere in lower-latitude Brunhes PSV records of similar resolution (e.g., Channell et al., 2012). U-channel measurements replicate PSV, excursions, and the placement of the Brunhes/Matuyama boundary documented with shipboard measurements. All of these observations suggest that a paleomagnetic chronostratigraphy, which we have developed, can be a useful tool for local correlation and relative dating among all the Bering Sea sites.

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Figure Captions

Figure 1: Northern Hemisphere polar region showing the IODP Expedition 323 coring sites. Also shown is the current geomagnetic field intensity with high-intensity foci associated with the North American and East Asian flux lobes noted (International Geomagnetic Reference Field 2000, Manda and Macmillan, 2000). Also shown are other high-latitude paleomagnetic records of Brunhes field variability (see Table 1).

Figure 2: Zijderveld diagrams showing the alternating field (AF) demagnetization of four u-channel horizons. The solid (open) circles in the Zijderveld diagrams indicate the vertical (horizontal) tip of a directional vector at each step in AF demagnetization. The numbers (20 to 100) indicate the mT step of the af demagnetization process. Dashed lines indicate the ideal straight-line path of demagnetization toward the origin with increasing mT AF levels.

Figure 3: Comparison of shipboard paleomagnetic measurements (open circles, 20 mT AF) and u-channel paleomagnetic measurements (solid circles, 20 mT AF) for two intervals of Brunhes paleomagnetic field behavior. Note the close correspondence between the shipboard and u-channel measurements.

Figure 4: Paleomagnetic records of Excursion 7a from Holes U1343C and U1344 E. Dashed lines indicate three times when either inclination or declination go through large changes while the other component is almost static.

Figure 5: Paleomagnetic records of the Brunhes/Matuyama polarity transition in Holes U1341A and U1343C. The open circles are shipboard data (demagnetized at 20 mT) and the closed circles are u-channel measurements demagnetized at 20 mT. The estimated locations of oxygen isotope stages 19-21 are indicated based on rock magnetic evidence for glacial/interglacial variations (high/low magnetic susceptibility goes with interglacial/glacial conditions).

Figure 6: Comparison of magnetic susceptibility (χ) and relative paleointensity (NRM 20 mT/ χ) for Hole U1345A. Selected peaks in χ and relative paleointensity, which can be correlated among the Bering Sea sites, are labeled. The oxygen isotope stratigraphy for this hole (Marine Isotope Stage (MIS) 1-13; Cook et al., in this issue) is shown for comparison.

Figure 7: Paleomagnetic chronostratigraphic framework for Bering Sea sites. (A) Correlatable relative paleointensity and magnetic susceptibility (Takahashi et al., 2011) features are plotted against the master record of Site U1344. Two paleomagnetic isochrons based on directional variability, Excursion 7a and the Brunhes/Matuyama boundary, are shown for comparison. Placement of oxygen isotope stages 5-13 are noted at top (Cook et al., in this issue). (B) The resulting age/depth relationships for all sites are plotted together (based on data in Table 2).

Figure 8: Paleomagnetic inclinations and declinations for a 10 meter interval of Site U1344 within oxygen isotope stage 9. 21 numbered inclination features and 17 numbered

declination features can be correlated among the three holes at this site. Grey bars indicate anomalous secular variation intervals where very high inclinations are paired with declinations that swing dramatically to the west. We think this is due to dominance of the East Asia flux lobe at select times.

Figure 9: (A) Unit-vector distribution of paleomagnetic directions from Hole 1344A within the Brunhes Chron. A white circle represents the vector mean direction. All excursions associated with Excursion 7a have been removed from this analysis. (B) Distribution of all Hole U1344A inclinations as a function of relative paleointensity. (Excursion 7a inclinations are included in this analysis.) The solid line indicates site axial dipole expectation.

Figure 10: (A) ΔI anomaly for one hole at each Bering Sea site (stars). Other results are summarized in Lund (2007). (B) VGP angular dispersion for one hole at each Bering Sea site (stars). Other results are summarized in Lund (2007).

Table 1: Brunhes Records of High-Latitude Field Variability

Site	Latitude	Brunhes Sed. (CCSF (m))	Sed. Rate (cm/ky)
ODP Leg 162			
980	55.0°N	87	11.1
981	55.0°N	55	7.0
982	57.5°N	20	2.5
983	60.0°N	91	11.5
984	60.5°N	108	13.8
IODP Expedition 302			
M0002A/4A	87.9°N	14.3	1.8
IODP Expedition 303/306			
U1302/3	50.2°N	115	14.7
U1304	53.3°N	140	17.9
U1305	57.5°N	125	16.0
U1306	58.2°N	120	15.4
U1307	58.5°N	35	4.5
U1314	56.3°N	60	7.7
IODP Expedition 323			
U1339	54.6°N	200	25.6
U1340	53.4°N	135	17.3
U1341	54.0°N	90	11.5
U1342	54.8°N	28	3.6
U1343	57.6°N	205	26.3
U1344	59.1°N	300	38.5
U1345	60.1°N	170+ [#]	25.0

[#] U1345 coring did not reach the Brunhes/Matuyama boundary.
The site has at least 170 m of Brunhes-aged sediment.

Table 2: Magnetic Correlation/Chronostratigraphy of IODP Ex. 323 Sites.

			U1339	U1340	U1341	U1342	U1343	U1344	U1345
FEATURE#	AGE(MA) *	CCSF (m)	CCSF (m)	CCSF (m)	CCSF (m)	CCSF (m)	CCSF (m)	CCSF (m)	CCSF (m)
surface	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CHI-A		1.0	1.0			1.0	1.0	0.5	
PI-1*		1.0				2.0	2.0	2.0	
term YD	0.015					4.0	5.0	2.0	
CHI-B		3.0		1.0		6.0	6.0	3.0	
onset YD	0.013					6.7	7.0	3.0	
PI-2		6.0				7.0	7.0	6.0	
MIS 2/3	0.024					9.3	13.0	8.5	
CHI-C		9.0		4.0		12.0	15.0	10.0	
MIS 3/4	0.059					15.2	18.0	11.5	
CHI-D=PI3a		10.0	11.0	8.0	2.5	23.0	34.0	20.0	
MIS 4/5	0.071	20.5						23.5	
CHI-E=PI3b	0.110	29.0	16.0	13.0	3.5	32.0	52.0	27.0	
MIS 5/6	0.131	34.5						35.0	
CHI-F		44.0	22.0	18.0	4.3	41.0	67.0	39.0	
PI-4	0.150	52.0	26.0	23.0	4.8	47.0	73.0	43.0	
MIS 6/7	0.191	54						48.0	
exc 7a	0.192	55?	32.5?			50.5	76.5		
Pi-4'	0.195	55.0	29.0	27.0	5.5	56.0	78.0	50.0	
CHI-G		57.0	30.0	28.0	5.8	56.0	80.0	52.0	
CHI-H		60.0	33.0	29.0	6.0	61.0	85.0	58.0	
PI-5	0.230	66.0	39.0	30.0	6.2	65.0	95.0	63.0	
CHI-I		67.0	40.0	30.0		66.0	96.0	64.0	
MIS 7/8	0.244	70.5						68.5	
CHI-J		75	43.0	32.0		72.0	105.0	70.0	
CHI-K=PI5'	0.300	77.0	47.0	33.0	8.5	82.0	113.0	80.0	
MIS 8/9	0.303	83.0						87.0	
PI-6	0.315	83.0	52.0	36.0	10.0	88.0	125.0	91.0	
CHI-L		84.0	53.0	36.0	10.3	90.0	125.0	91.0	
MIS 9/10	0.336	92.0						98.5	
CHI-M			57.0	38.0	11.5	99.0	138.0	100.0	
MIS 10/11	0.375	98.5						115.5	
PI-7	0.410	106.0	59.0	40.0	12.8	106.0	150.0	112.0	
CHI-N			63.0	42.0	13.0	108.0	155.0	115.0	
MIS 11/12	0.425	112.0						130.5	
PI-7'	0.430		66.0	44.0	14.3	117.0	162.0	125.0	
excursion						123.0		125.0	
CHI-O			73	46	14.75	123	173	132	
MIS 12/13	0.473	123.7						148.5	
PI-8	0.505	126.0	79.0	50.0	15.3	135.0	195.0	155.0	
CHI-P			82.0	51.0	15.5	136.0	197.0	157.0	
CHI-Q			86.0	53.0		142.0	203.0		
CHI-R			89.0	56.0		148.0	211.0		
CHI-S			90.0	58.0		154.0	218.0		
CHI-T=PI9			95.0	60.0	18.3	158.0	230.0		
CHI-U			98.0	63.0		165.0	240.0		
CHI-V=PI10			109.0	73.0	21.0	170.0	247.0		

597	CHI-W					177.0	258.0
598	CHI-X			115.0		183.0	269.0
599	CHI-Y					186.0	280.0
600	CHI-Z					190.0	285.0
601	CHI-AA=PI11			123.0	80.0	24.5	195.0
602	CHI-BB			125.0	82.0	26.0	200.0
603	CHI-CC			129.0	84.0	26.5	205.0
604	B/M	0.781	188.0	133.0	87.5	26.5	207.5
605	CHI-DD					28.0	209.0
606	excursion				65.8		320.0

607 #CHI = magnetic susceptibility features, PI = paleointensity feature, YD = Younger
608 Dryas, numbers indicate oxygen isotope stage boundaries (U1339 and U1345 depths
609 from Cook et al. (this issue).
610 *Ages for excursions are estimated by Lund et al. (2006). Ages of oxygen isotope
611 boundaries are estimated from Lisiecki and Raymo (2005), see also Cook et al. (this
612 issue).

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Figure 1

Figure 2

Figure 3

Figure 4

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Figure 6

Figure 7

Figure 8

Figure 9

Figure 10