Redefinition of the Blake Event

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Abstract

We have recovered four new records of the paleomagnetic field variability within Oxygen Isotope Stage 5 from deep-sea sediment cores of the Blake/Bahama Outer Ridge, western North Atlantic Ocean. These cores contain reproducible evidence of the Blake Event and are located within 300 km of cores used by Smith and Foster (1969) to define the Blake Event. Our new paleomagnetic records have both reproducible directions and relative paleointensities, but they should be considered only medium-resolution records because they were recovered from sediments with bulk accumulation rates of only ~6 cm/kyr. The paleomagnetic records are complicated by the fact that the Blake Event occurs within a narrow zone of bacterial magnetite. Our rock magnetic and paleomagnetic studies suggest that the bacterial magnetite has not contributed significantly to the directional or relative paleointensity results. We propose that our four new paleomagnetic records be used to redefine the Blake Event because these records significantly improve our understanding of the age and paleomagnetic field variability associated with the Blake Event in its type area. Our records indicate that the Blake event occurred ~119-126,000 years BP, within Oxygen Isotope Stage 5e (114-131,000 years BP). The Blake Event is a local magnetic field reversal (Class II excursion) with directions flipping quickly to reversed-polarity directions, hovering statically for at least 6000 years, and then flipping quickly back to normal polarity directions. The core dynamo source for the Blake Event must have a strong axisymmetric and global-scale character to produce such a true local polarity reversal.

Introduction

Geomagnetic field excursions are defined as short intervals of locally anomalous field directions that occur within a broader interval of 'stable' (normal or reversed) magnetic polarity. By anomalous, we mean that the directions have equivalent virtual geomagnetic poles (VGPs) more than 45° away from the geographic North (South) Pole during normal (reversed) polarity (Watkins, 1976; Verosub and Banerjee, 1977). (VGPs are calculated from local magnetic field directions that locate the magnetic-field North Pole by assuming that the directions are caused by a simple dipole or bar magnet situated at the center of the Earth.) There have been enough independent paleomagnetic records of excursions documented (e.g.; Champion et al., 1988; Nowaczyk and Baumann, 1992; Langereis et al., 1997; Lund et al., 1998, 2001) to be confident that excursions really do exist and are a fundamental aspect of geomagnetic field variability.

We need to understand the detailed pattern of spatial and temporal variability associated with excursions if we are going to estimate what excursions indicate about the outer-core dynamo process that generates them. Three of the best-known and most recent excursions are the Mono Lake Excursion (Denham and Cox, 1971; Liddicoat and Coe, 1979) (ca. 33,000 cal. yrs. BP), Laschamp Excursion (Bonhommet and Babkine, 1967) (ca. 41,000 cal. yrs. BP), and Blake Event (Smith and Foster, 1969) (ca., 119,000 cal. yrs. BP). For all of these excursions, there are continuing arguments about their space/time pattern of field variability and their relationships to both normal secular variation and the geomagnetic field reversal process.

Of these three excursions, the Blake Event is the most poorly defined in its type locality (Blake/Bahama Outer Ridge, western north Atlantic Ocean, Figure 1) with lingering questions about the Blake event's exact age, duration, and pattern of directional variability. In this paper, we present new paleomagnetic and chronostratigraphic results from four deep-sea sediment piston cores from the Blake/Bahama Outer Ridge that redefine its age and directional variability in the type locality and significantly improve our overall understanding of the Blake Event.

Previous Paleomagnetic Records of the Blake Event

Smith and Foster (1969) defined the Blake Event on the basis of paleomagnetic studies of four deep-sea sediment cores from the Blake Outer Ridge (16°N-32°N), western North Atlantic Ocean (Figure 1), two cores from the Caribbean Sea (16°N), and one core from the Indian Ocean (28°S). However, the paleomagnetic directions in these seven cores were not exactly reproducible between cores so that the only clear indication of the excursion was the presence of anomalous inclination values. Minimum inclination values were -10° to -70° in different cores from the Northern Hemisphere, while their expected average inclinations are near +40°. Only two of the seven cores had declination data, which did not agree in detail, and none had associated estimates of paleointensity variation. The original age estimate for the Blake Event was determined on the basis of the X-zone microfossil assemblage and a radiometric age of 126,000±6,000 cal. yrs. BP for its base. The Blake Event age was estimated to be 108-114,000 cal. yrs. BP based on linear interpolation of average sedimentation rates in three cores.

The best evidence for the age of the Blake Event at its type locality, about 115,000 cal. yrs. BP (Stage 5d/5e transition), comes from later analyses by Wollin et al. (1971) and Ryan (1972) using oxygen isotope measurements from the same cores studied by Smith and Foster (1969). Later work by Denham and colleagues (Denham, 1976; Denham et al., 1977) provided corroborating evidence for the Blake Event from deep-sea sediments of the Greater Antilles Outer Ridge, western North Atlantic Ocean (~500 km SE of the Blake/Bahama Outer Ridge) and provided the first evidence that the Blake Event might contain two intervals of almost reversed polarity, each more than 1000 years in duration and separated by more than 1000 years of normal polarity. Unfortunately, their chronology was too poor to better resolve either absolute ages or reversed polarity durations.

Subsequently, many other workers have found evidence for existence of the Blake Event (or another independent excursion nearly the same age as the Blake Event) around the world: Japan (Lake Biwa - Kawai, 1984; volcanics - Sasajima et al., 1984), China (lavas - Chun et al., 1983; loess - Zhu et al., 1994; Fang et al., 1997), Amazon fan (Cisowski, 1995), western USA (lavas - Champion et al., 1988), Hawaii (lavas -Holt et al.,1996), Mediterranean Sea (Ryan, 1972; Tucholka et al., 1987; Tric et al., 1991; Langereis et al., 1997), Arctic Ocean (Nowaczyk and Baumann, 1992; Nowaczyk et al., 1994), Iceland Basin (Bleil and Gard ,1989; Nowaczyk and Frederichs, 1999), and the Indian Ocean (Smith and Foster, 1969). The best lava-flow data suggest a radiometric age for the Blake Event of ~130,000 cal. yrs. BP, but the dates have large age uncertainties (e.g.; 128,000±33,000 cal. yrs. BP from Champion et al., 1988; 132,000±32,000 cal. yrs. BP from Holt et al., 1996). The sediment records provide ages that range from less than 110,000 cal. yrs. BP (e.g., Ryan, 1972; Tric et al., 1991) to greater than 130,000 cal. yrs. BP (Bleil and Gard, 1989; Nowaczyk and Fredericks, 1999). Most sediment studies suggest that the Blake Event occurs within oxygen isotope Stage 5e, but selected studies (Tucholka et al., 1987; Tric et al, 1991) place the Blake Event at least partly within Stage 5d and others (Bleil and Gard, 1989; Nowaczyk and Fredericks, 1999) place it below the Stage 5/6 boundary. The sediment studies also estimate durations of the Blake Event that range from 1000 to 8000 years and nearby records may differ in estimated duration by more than a factor of two (e.g., Tucholka et al., 1987; Nowaczyk and Baumann, 1992). Overall, these paleomagnetic studies of the Blake Event still leave the age and duration of the Blake Event as well as its exact pattern of field variability somewhat unresolved.

New Paleomagnetic Records of the Blake Event

We have recovered four new deep-sea sediment piston cores (JPC15, JPC17, JPC18, and JPC22) from the Blake/Bahama Outer Ridge (Figure 1; Table 1) that contain paleomagnetic records of the Blake Event. These cores are located within ~300 km (Figure 1) of the cores (RC 7-2, RC 11-256, RC 7-4) studied by Smith and Foster (1969). We have carried out detailed paleomagnetic and rock magnetic studies to define the pattern of directional and paleointensity variability associated with the Blake Event and with the normal secular variation that surrounds the Blake Event. We have also used several independent sedimentologic and chronostratigraphic methods to correlate and date the records to better than ~±1000 year resolution.

Chronostratigraphy:

Initially, we used two sedimentologic parameters, magnetic susceptibility and calcium carbonate percentage, to cross-correlate the cores and to correlate them with previously studied cores from the same region. We have previously carried out paleomagnetic, rock magnetic, and sedimentologic studies on a transect of deep-sea sediment cores, which extend the length of the Blake/Bahama Outer Ridge (Schwartz et al., 1997). We have measured magnetic susceptibility on all cores and calcium carbonate percentage (Johnson et al., 1988; Keigwin and Jones, 1989; Haskell et al., 1991) on selected cores. We used paleomagnetic field variability (both directions (Lund et al, 2001) and paleointensity (Schwartz et al., 1998)), radiocarbon dates (Johnson et al., 1988; Keigwin and Jones, 1989), and oxygen isotope stratigraphy (Keigwin and Jones, 1989; Keigwin et al., 1994) from selected cores to provide a time stratigraphic framework for these measurements.

Figure 2 shows the magnetic susceptibility stratigraphy of our four new cores and two previously studied cores (JPC37, CH88-10P) together with the locations of oxygen isotope boundaries for Stages 1-6. All of our chronostratigraphic indicators (including our new paleomagnetic directional and paleointensity data discussed below) suggest that the detailed variability in magnetic susceptibility, notable in Figure 2, is synchronous (~±200 years relative age) over the spatial domain of the Blake/Bahama Outer Ridge. Figure 3 displays a blow-up of the Stage 5 magnetic susceptibility variability for these same cores. Selected susceptibility features that we think are correlatable are numbered 1-17. Also, the placement of six calcium carbonate peaks (A1-E1) that occur in Stage 5 are noted by vertical bars. The labeling and age assignment of these carbonate peaks follows the work of Keigwin et al. (1994) on deep-sea sediment core GPC9 that is summarized in Figure 4. GPC9 was collected from the same location as two of our studied cores, JPC17 and JPC22 (Table1). The placement of the carbonate peaks is everywhere consistent with the labeled magnetic susceptibility variability.

Detailed records of magnetic susceptibility, carbonate stratigraphy, and oxygen isotope stratigraphy (selected records) are shown for cores GPC9, JPC37, JPC18, and JPC22 in Figures 4-6. All of these records are consistent in their chronostratigraphic and sedimentologic variability. On the basis of these detailed records, we have delineated the location of Stage 5e (which totally contains the Blake Event in our records). We follow Martinson et al. (1987) and assign an age interval of 114-131,000 cal. yrs. BP to Stage 5e.

Paleomagnetic Studies:

Paleomagnetic samples were taken throughout the Stage 5 sections of cores JPC15, JPC18, and JPC22. The normal sampling procedure was to take a 2x2x2 cm cube every 2.5 cm stratigraphically from the center of the split core using a square-cross-section cutting tube (e.g., Lund, 1981) to minimize sediment distortion. Because the cores were large in diameter (20 cm), sample cubes were taken in two parallel columns, with a 1.25 cm offset, through the Blake Event interval in core JPC22. The two parallel columns of sediment cubes were still collected at least 2.5 cm from the edges of the core, so that we were not concerned with effects of core edge distortion associated with coring. Core JPC15 was sampled every 2.5 cm only through the Blake Event interval, based on magnetic susceptibility correlations to the nearby core JPC22.

The natural remanent magnetization (NRM) of all sediment cubes was initially measured and then selected sediment cubes outside the Blake Event interval and all sediment cubes within (or less than 10 cm outside) the Blake Event interval were step-wise alternating-field (a.f.) demagnetized and measured at 10 mT intervals up to 100 mT. Typical Zijderveld diagrams for selected horizons are shown in Figure 7. Almost all samples lost a small to medium intensity remanence between 0 and 20 mT that we interpret to be a viscous overprint residing in the coarsest magnetic grains (magnetite to low titanium titanomagnetite (Schwartz et al., 1997, 1998)). The samples then routinely display the decay of a characteristic remanence (ChRM, single direction) with continued demagnetization between 20-30 mT and 80-90 mT. All pilot samples outside the Blake Event interval yielded ChRM directions not significantly different from the 20-mT direction and so all other samples were demagnetized only at 20mT and 40 mT. Above 80-90 mT, there was usually a ~1-5% remanence that had slightly to significantly different directions than the ChRM. The possible cause of this different direction will be discussed below.

The final paleomagnetic results for all samples outside the Blake Event interval are reported as directions after 20-mT a.f. demagnetization. There was no significant difference between these values and their 40-mT values or ChRMs for samples that had more complete a.f. demagnetization. All paleomagnetic results for samples within (or less than 10 cm outside) the Blake Event are reported as ChRMs based on linear least-squares interpolation through the data from 30-80 mT. (Almost all ChRMs had MAD values less than 5°; see below for more complete discussion.) Paleomagnetic inclination and declination data for cores JPC17, JPC18, and JPC22 are displayed in Figure 8. The Blake Event data have been removed to permit closer inspection of the more subtle secular variation surrounding the Blake Event. Figure 8 shows 29 inclination and 27 declination features that appear to be correlatable. These scalar correlations are consistent with each other (preserve inclination and declination phase relationship) and with the magnetic susceptibility and carbonate correlations noted earlier.

Given that Stage 5 is ~60,000 years in duration, the 56 correlatable inclination and declination features indicate that millennial-scale secular variation is preserved in these cores. However, the average Stage 5 sedimentation rate in these cores is typically 6-8 cm/kyr (Table 1). Therefore, these secular variation records cannot be considered high in resolution; at best, they are medium-resolution records with some moderate degree of sediment smoothing of the original input secular variation signal. Lund and Keigwin (1994) have previously studied a similar case of sediment paleomagnetic smoothing in Holocene sediments from the Bermuda Rise, western North Atlantic Ocean (similar sediment types and sedimentation rates). Their conclusions were that smoothing tended to be frequency dependent, such that shorter duration paleomagnetic variability was preferentially smoothed (or averaged) leaving longer duration variability somewhat preserved. We would certainly agree that our Stage 5 paleomagnetic records from the Blake/Bahama Outer Ridge have some moderate amount of smoothing of the original paleomagnetic signal, but we believe that the signal loss is biased to the higher frequency components, so that the millennial-scale variability still present in Figure 8 is a reasonable estimate of millennial-scale field variability during Stage 5.

Rock Magnetic Studies:

The rock magnetic properties of these sediments have been studied previously by Schwartz et al. (1996, 1997, 1998). The sediments are hemipelagic clays, rich in iron-bearing mineral phases, with variable carbonate percentage (Figures 5, 6). The predominant magnetic phase carrying the NRM is interpreted to be magnetite or a low-titanium titanomagnetite (Schwartz et al., 1997, 1998). However, there are other remanent magnetic minerals present in small proportions (goethite, hematite, biogenic magnetite) that may contribute partially to the NRM under special circumstances.

The rock magnetic stratigraphy of core JPC 18 (Stages 4, 5 and late Stage 6) is shown in Figure 9. This rock magnetic stratigraphy is also typical of JPC15, JPC17, and JPC22 (as well as those cores studied by Schwartz et al. (1996, 1997, 1998)). High magnetic susceptibility, SIRM (saturation isothermal remanence), and ARM (anhysteretic remanence) near 12 m document the Stage 4/5 transition and return to glacial conditions with lowered sea level and increased clastic flux to the North Atlantic Ocean. The general decrease in these parameters from 17-15 m marks the transition from glacial Stage 6 (low sea level and high clastic flux) to Stage 5 with higher sea level, lower clastic flux and higher carbonate content.

The primary complication to these records is that they all contain two narrow intervals of biogenic (bacterial) magnetite (BM) within the Stage 5 sediments (gray zones in Figure 9). Each of these intervals is noted by the presence of anomalously high ARM/Chi ratios, ARM intensities, and ARM coercivities, and is associated with a high carbonate interval (either C1 or E1), noted in Figures 3-6. The two BM zones range from 30 to 60 cm in thickness; the BM intervals in JPC17 and JPC22 are 20-30 cm thick while those in JPC15 and JPC18 cores are 40-60 cm thick. (The exact placement of these BM intervals relative to the Blake Event is discussed and pictured below.) Selected magnetic separates have been recovered from two of these intervals in cores JPC22 and JPC18. Transmission-electron microscopy (TEM) clearly shows the presence of euhedral ~0.1 μm crystals of iron-bearing (but no sulfur or titanium) material. Similar TEM pictures from Holocene sediments of the Blake/Bahama Outer Ridge were previously published by Schwartz et al. (1997).

We interpret these BM intervals to be paleoredox boundaries associated with times of relatively high organic flux associated with the high (biogenic) carbonate intervals. The 2 BM intervals in cores JPC15 and JPC18 are thicker because they occur at shallower water depths (~4000 m) and probably had high enough organic flux for longer time intervals associated with the high carbonate intervals to produce a more significant pattern of early sediment diagenesis leading to sulfate reduction. Cores JPC17 and JPC22, on the other hand, have two narrower BM intervals because the cores come from deeper water (~4500 m) and less organic material reaches the bottom sediments.

Schwartz et al. (1997) have investigated, in detail, a modern (Holocene, Stage 1) analog of these BM intervals on the Blake/Bahama Outer Ridge. They concluded that the current Holocene (Stage 1) sedimentation throughout the Blake/Bahama Outer Ridge, which is high in carbonate and organic flux, has associated with it an ambient redox gradient that reaches Mn and Fe reduction at the base of the high carbonate interval and sulfate reduction below that. This ambient redox gradient supports an active population of magnetite-bearing bacteria in the suboxic zone of high carbonate above the Mn/Fe redox front. This zone has almost identical rock magnetic characteristics to those of the Stage 5 BM intervals. The iron for the biogenic magnetite (and a narrow ferric-iron front below it) comes primarily from dissolution of mobile ferric-iron phases (goethite, hematite, iron-oxyhydroxides) and not from the noticeable dissolution of remanent ferromagnetic phases. It is important to note that Schwartz et al. (1997) see no evidence that the biogenic magnetite plays a significant role in the sediment natural remanence. The Holocene high biogenic-magnetite zone is one that has a minimum in NRM intensity with no evidence for significant NRM intensity changes at the boundaries of the BM interval. They argue that the biogenic magnetite particles electrostatically couple to clay particles on death and dissaggregation of the magnetite chains and do not efficiently align with the ambient magnetic field. We would argue the same situation for the Stage 5 BM intervals. We see no evidence for significant increases in NRM intensity as one goes into or out of the various BM intervals and the secular variation (and Blake Event variability) is the same between cores even though one core has BM and another core does not. We will discuss this in more detail below for the Blake Event itself.

Sediment Relative Paleointensity Studies:

The Stage 5 sediments are not ideal for recovering relative paleointensity records because they have two BM intervals where selected rock magnetic parameters are significantly different (Figure 9). Also, the Stage 5 rock magnetism outside the BM intervals is significantly different from that in Stages 4 and 6 (Figure 9) in overall intensity, so any relative paleointensity record within Stage 5 may have discontinuities at the stage boundaries associated with rock magnetic changes. Even so, we have used techniques of Schwartz et al. (1998) to develop relative paleointensity records from the four study cores in order to provide some constraint on potential paleointensity changes associated with the Blake Event. We have normalized the sediment NRM (20 mT) by magnetic susceptibility, ARM (20 mT), and SIRM (20 mT). The magnetic susceptibility and SIRM normalizations are almost identical and we have used the NRM(20mT)/SIRM(20mT) ratio as our preferred relative paleointensity estimate. The ARM (20mT) normalized paleointensity estimate is similar to the other two outside the BM intervals, but inside these intervals it predicts anomalously low values due to anomalously strong ARM intensities associated with the BM.

The NRM20/SIRM20 relative paleointensity records for our four studied cores are shown in Figure 10, together with our previously published record from CH88-10P (Schwartz et al., 1998). The records have all been renormalized to an average intensity of one. Twenty-six distinctive and correlatable paleointensity features can be identified in Figure 10. These correlations corroborate the overall quality and reproducibility of the paleointensity records. The paleointensity decrease from feature 26 to feature 23 occurs across the Stage 5/6 boundary (16 m in JPC18) and is consistent in pattern with the relative paleointensity pattern seen in other published records from the North Atlantic Ocean (e.g., Stoner et al., 1998). By contrast, the relative paleointensity increase from feature 11 in Stage 5 to features 5/6 in Stage 4 is not consistent among the records. The paleointensity increase in JPC18 is consistent with other published records (e.g., Stoner et al., 1998), but the paleointensity increase in JPC22 and CH88-10P appears to be too high relative to average paleointensity values in Stage 5. It is likely that there is a significant change in rock magnetic properties across the Stage 4/5 boundary in these cores (indicated by dashed lines in Figure 10) that changes the relative paleointensity baseline. Such baseline shifts have been noted previously in other published relative paleointensity records (e.g., Schwartz et al., 1998; Stoner et al., 2003).

The Stage 5 relative paleointensity records for the four cores are plotted with the Blake Event directional results in Figures 11-14. The gray regions in each core indicate the locations of the BM intervals. The overall paleointensity variability appears to be largely unaffected by the

BM intervals. In each of the cores, the relative paleointensity values on either side of the BM boundaries are not significantly different. Thus, there is no significant evidence for an apparent change in paleointensity that might be due to presence or absence of single-domain magnetite. This implies that the BM is not contributing significantly to the NRM, as was noted by Schwartz et al. (1997), and that its contribution to magnetic susceptibility and SIRM is not sufficient to significantly alter the paleointensity estimates across BM interval boundaries.

Field Behavior During the Blake Event

We can now use the paleomagnetic directional and relative paleointensity results in Figures 11-14 to assess the pattern of geomagnetic field variability associated with the Blake Event. The Blake Event itself is defined as the interval of anomalous directions identified as declination feature 25 and inclination feature 26 in Figures 11-14. The Blake Event occurs within an interval of relatively low paleointensity associated with intensity features 23-24', but the low paleointensity is not one of the defining elements of the Blake Event.

The Blake Event starts with a discontinuous shift in declinations from normal values near 0° (feature 26) to values almost 180° away. The declinations within feature 25 hover near 180° for 20-30 cm and then the declinations make another step back to normal values in feature 24. The termination of feature 25 is not as discontinuous as its onset, and individual declination values suggest some sense of an oscillatory transition from anomalous to normal directions. One problem with the declinations, which we will address later, is that the declination values in the onset and termination transitions are easterly (30° to 150°) in JPC17 and JPC18, but westerly (-30° to –150°) in JPC15 and JPC22. Both cannot be right.

The inclinations behave in a similar manner to the declinations. The inclinations reach relatively high values near 60° in feature 27 and then abruptly change to values near the site reversed-polarity axial-dipole expectation (~-50°) in feature 26. This happens at the same time as the declinations make their initial discontinuous shift to values near 180°. The inclinations in feature 26 hover near –50° for 20-30 cm and then step back to high positive values (~60°) in feature 24. As with the declinations, there is some sense of an oscillatory transition from anomalous back to normal inclinations.

The virtual geomagnetic poles (VGPs) associated with the Blake Event directions are plotted in Figure 15. These identify the sequence of instantaneous North Magnetic Poles associated with the paleomagnetic directions, assuming that each direction was due solely to a dipole field. If the results from the four cores were identical, then they would all show the same VGP path. The four cores do show that the Blake Event is dominated by directions that are reversed in polarity with VGPs hovering near the South Pole. But, cores JPC17 and JPC18 display a VGP path through Africa as the field entered and then terminated the Blake Event, while cores JPC15 and JPC22 display a VGP path (less clear) that went through East Asia. This difference is due to the different transitional declinations noted above.

We believe that neither of the transitional VGP paths may be real, given that these paleomagnetic records are not high in resolution with sedimentation rates of only about 5 cm/ky in Stage 5e (Table 1). The transitional directions at the onset and termination of the Blake Event occur in intervals that have the lowest relative paleointensity (features 23 and 24') of all of Stage 5. We believe that the low paleointensities and transitional directions are due to a mixture of different transitional directions locked in over a period of ~1000 years (~5 cm) within each sample. Subtle differences in smoothing interval and sedimentation rate cause the two different apparent transitional VGP paths.

We do believe that the general pattern of the Blake Event is real. The Blake Event appears to be a local full reversal of the geomagnetic field that occurs between ~119-126,000 years BP in the middle of Stage 5e. The field reverses quickly (<1000 years?), hovers at full-reversed polarity (South Pole) for about 6000 years (Table 1) and then quickly flips back to normal polarity values. We think that the millennial-scale characteristics of the Blake Event are reproducible and reasonably accurate even though the higher frequency variability within the sharp transition onset and termination may not be accurate. This is consistent with the effects of sediment smoothing on magnetic remanence noted by Lund and Keigwin (1994).

Two characteristics of the Blake Event deserve special note. First, the excursional inclinations and declinations flip polarity in phase (at the same time), to the limit of our resolution. Within the excursion, the directions hover somewhat statically near the South Pole for almost 6000 years. This dynamical evolution of the excursion is quite distinct from that of the Mono Lake (e.g., Liddicoat and Coe, 1979) or Laschamp Excursion (e.g., Lund et al., in press). In those excursions, which Lund et al. (in press) term Class I, the dynamical evolution is such that inclination and declination variations are composed of millennial-scale cycles with near 90° out-of-phase relationships that produce large-scale looping of the directions and VGPs. Intervals with true excursional directions are limited to only a few hundred years. The Blake Event is quite different from these excursions and we think it falls within a separate category of excursions, which we term Class II (Lund et al., 1994).

The second characteristic of the Blake Event that deserves special note is that its reversed-polarity directions obey a global-scale model of an axial dipole. That is, the declinations hover near 180°, exactly antipodal to the normal polarity directions on either side of the excursion. More importantly, the inclinations flip from near axial-dipole normal polarity values of about +50° to antipodal reversed-polarity inclinations of –50°. Thus, during the Blake Event, the reversed-polarity local field must be generated by a source that keeps account of the local site latitude (to get the inclination right) and location of the North Pole (to get the declination right). That source must contain a global-scale sense of axial symmetry like an axial dipole. Such a source could be a convection roll (e.g., Bloxham and Gubbins, 1989) that has reversed its polarity. The source cannot be one localized in an outer-core region near the site of the Blake/Bahama Outer Ridge, such as a dynamo wave or convection eddy, for they won't produce the observed directional pattern of the Blake Event.

Conclusions

We have recovered four new records of the paleomagnetic field variability (both directions and relative paleointensity) within Oxygen Isotope Stage 5 from deep-sea sediment cores of the Blake/Bahama Outer Ridge, western North Atlantic Ocean. These cores contain reproducible evidence of the geomagnetic-field Blake Event and are located within 300 km of cores used by Smith and Foster (1969) to define the Blake Event. The four cores have been correlated with each other and with other previously studied cores from the region using magnetic susceptibility variations and carbonate stratigraphy, and they have been dated using oxygen isotope stratigraphy. Our new paleomagnetic records are reproducible among the four records, but they should be considered only medium-resolution paleomagnetic records because they were recovered from sediments with bulk sediment accumulation rates of only ~6 cm/kyr. The paleomagnetic records are complicated by the fact that the Blake Event occurs with one of two narrow zones of bacterial magnetite. Our current and previous rock magnetic studies (Schwartz et al., 1997) suggest that the bacterial magnetite has not contributed significantly to the directional or relative paleointensity results.

We propose that our four new paleomagnetic records be used to redefine the Blake Event, in as much as these records come from the type area of the Blake Event as defined by Smith and Foster (1969) and significantly improve our understanding of the age and paleomagnetic field variability associated with the Blake Event in its type area. Our records indicate that the Blake event occurred ~119-126,000 years BP, within the middle of Oxygen Isotope Stage 5e (114-131,000 years BP). The Blake Event is a local magnetic field reversal (Class II excursion) with directions flipping quickly (<1000 years?) to reversed-polarity directions (D~180°, I~-50°), hovering statically for at least 6000 years, and then quickly flipping back to normal polarity directions (D~0°, I~+50°). The dynamo source for the Blake Event in the Earth's core must have a strong axisymmetric and global-scale character to produce such a true local polarity reversal.

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Figure Captions

Figure 1: Map of the Blake/Bahama Outer Ridge, western North Atlantic Ocean showing the locations of deep-sea sediment cores discussed in this study. Cores RC7-2, RC7-4 and RC11-256 were used by Smith and Foster (1969) to define the Blake Event.

Figure 2:Magnetic susceptibility variations in selected deep-sea sediment cores from the Blake/Bahama Outer Ridge. Locations of Oxygen Isotope Stages 1-6 are indicated by dashed lines and correlated among the cores.

Figure 3: Expanded records of magnetic susceptibility variations within Stage 5. Seventeen correlatable susceptibility features are noted. The placement of six distinctive calcium-carbonate peaks (labeled A1-E1 at the figure bottom) is indicated by vertical line segments in each core.

Figure 4: Carbonate and oxygen isotope stratigraphy for core GPC9. Distinctive carbonate peaks are labeled A1-E1. Dashed lines indicate the boundaries between Oxygen Isotope Stages 5a-5e.

Figure 5: (Top) Carbonate and oxygen isotope stratigraphy in Stage 5 for core JPC37. (Bottom) Carbonate and magnetic susceptibility stratigraphy in Stage 5 for core JPC37. Carbonate peaks A1-E1 are labeled for clarity. Stage 5e is outlined by dashed lines.

Figure 6: (Top) Carbonate and magnetic susceptibility stratigraphy in Stage 5 for core JPC18. (Bottom) Carbonate and magnetic susceptibility stratigraphy in Stage 5 for core JPC22. Carbonate peaks A1-E1 are labeled for clarity. Stage 5e is outlined by dashed lines.

Figure 7: Zijderveld diagrams for selected horizons indicated by core and sediment depth. The closed (open) symbols represent the tips of paleomagnetic vectors projected into the horizontal X-Y (vertical Y-Z) plane. The Square represents the initial NRM and the circles represent the NRM at each step after A.F. demagnetization up to 100 mT. Notice a smooth straight-line demagnetization path (ChRM) for all horizons between 30 mT and 80 mT.

Figure 8: Stage 5 paleomagnetic inclinations (top) and declinations (bottom) from three of our cores (JPC15, JPC22, JPC18) and from one of our previous studies (CH88-10P) (Lund et al. 2001). The directions have been correlated and normalized to the sediment depth in JPC18. Selected inclination and declination features are labeled for comparison. The directional variability in the Blake Event was removed so that the more subtle PSV could be more easily seen and compared among the four cores.

Figure 9: Rock magnetism of core JPC18. The gray zones indicate intervals that have single-domain bacterial magnetite (BM).

Figure 10: Relative paleointensity from three of our cores and from CH88-10P (Schwartz et al., 1998). The paleointensity values are all 3-pt running averages and have been renormalized to unit mean. The dashed lines in cores CH88-10P and JPC22 indicate the Stage 4/5 boundary and a presumed change in paleointensity baseline. See text for further discussion.

Figure 11: Early Stage 5 paleomagnetic record (declination, inclination, relative paleointensity) from core JPC15 showing the Blake Event (declination feature 25, inclination feature 26, paleointensity features 23-24'). Carbonate peaks C1-E1, two bacterial magnetite intervals (gray regions), and Stage 5e (box at top) are delineated to provide correlation and chronostratigraphy.

Figure 12: Early Stage 5 paleomagnetic record (declination, inclination, relative paleointensity) from core JPC22 showing the Blake Event (declination feature 25, inclination feature 26, paleointensity features 23-24'). Carbonate peaks C1-E1, two bacterial magnetite intervals (gray regions), and Stage 5e (box at top) are delineated to provide correlation and chronostratigraphy.

Figure 13: Early Stage 5 paleomagnetic record (declination, inclination, relative paleointensity) from core JPC17 showing the Blake Event (declination feature 25, inclination feature 26, paleointensity features 23-24'). Carbonate peaks C1-E1, two bacterial magnetite intervals

(gray regions), and Stage 5e (box at top) are delineated to provide correlation and chronostratigraphy.

Figure 14: Early Stage 5 paleomagnetic record (declination, inclination, relative paleointensity) from core JPC18 showing the Blake Event (declination feature 25, inclination feature 26, paleointensity features 23-24’). The paleointensity record is the raw data (3-pt. average data are shown in Figure 10). Carbonate peaks C1-E1, two bacterial magnetite intervals (gray regions), and Stage 5e (box at top) are delineated to provide correlation and chronostratigraphy.

Figure 15:VGP paths for cores VPC15, JPC17, JPC18, and VGP22 (top to bottom) through the Blake Event.

Table 1: Deep-Sea Sediment Cores from the Blake/Bahama Outer Ridge

Core	Latitude	Longitude	Water Depth	Sed. Rate (Stage 5)	Sed. Rate (5e)	Blake
CH88-10P						
GPC9	28.25°N	78.41°W	4758 m	5.6 cm/kyr		
JPC15	28.59°N	74.20°W	4320 m	6.0 cm/kyr	5.0 cm/kyr	6.0 ky
JPC17	28.25°N	74.41°W	4715 m	7.5 cm/kyr	5.1 cm/kyr	6.8 ky
JPC18	27.82°N	74.11°W	4205 m	5.9 cm kyr	4.0 cm/kyr	7.5 ky
JPC22	28.25°N	74.41°W	4712 m	7.7 cm/kyr	4.5 cm/kyr	6.6 ky
JPC37	31.69°N	75.43°W	2972 m	7.7 cm/kyr		