New biostratigraphic, magnetostratigraphic and isotopic insights into the Middle Eocene Climatic Optimum in low latitudes

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Abstract

The Middle Eocene Climatic Optimum (MECO) was a warming event that interrupted the long-term Eocene cooling trend. While this event is well documented at high southern and mid-latitudes, it is poorly known from low latitudes and its timing and duration are not well constrained because of problems of hiati, microfossil preservation and weak magnetic polarity in key sedimentary sections. Here, we report the results of a study designed to improve the bio-, magneto- and chemostratigraphy of the MECO interval using high-resolution records from two low-latitude sections in the Atlantic Ocean, Ocean Drilling Program (ODP) Sites 1051 and 1260. We present the first detailed benthic foraminiferal stable isotope records of the MECO from the low latitudes as well as biostratigraphic counts of *Orbulinoides beckmanni* and new magnetostratigraphc results. Our data demonstrate a ~750 kyr-long duration for the MECO characterized by increasing $\delta^{13}C$ and decreasing $\delta^{18}O$, with minimum $\delta^{18}O$ values lasting ~40 kyrs at 40.1 Ma coincident with a short-lived negative $\delta^{13}C$ excursion. Thereafter, $\delta^{18}O$ and $\delta^{13}C$ values recover rapidly. The shift to minimum $\delta^{18}O$ values at 40.1 Ma is coincident with a marked increase in the abundance of the planktonic foraminifera *O. beckmanni*, consistent with its inferred warm-water preference. *O. beckmanni* is an important Eocene biostratigraphic marker, defining planktonic foraminiferal Zone E12 with its lowest and highest occurrences (LO and HOs). Our new records reveal that the LO of *O. beckmanni* is distinctly diachronous, appearing ~500 kyr earlier in the equatorial Atlantic than in the subtropics (40.5 versus 41.0 Ma). We also show that, at both sites, the HO of *O. beckmanni* at 39.5 Ma is younger than published calibrations, increasing the duration of Zone E12 by at least 400 kyr. In accordance with the tropical origins of *O. beckmanni*, this range expansion to higher latitudes may have occurred in response to sea surface warming during the MECO and subsequently disappeared with cooling of surface waters.

Keywords: Middle Eocene Climatic Optimum, Site 1051, Site 1260, planktonic foraminifera, biostratigraphy, magnetostratigraphy.

1. Introduction

Development of high-quality age models is essential for the reliable determination of sequences of events in the geological record, i.e., a geological timescale, for correlation of palaeorecords between sites, and for estimating rates of change in palaeoenvironmental records. Construction of a reliable geological time scale for the middle Eocene has been hindered by a lack of high quality sedimentary sections. In part, these difficulties arise from a relatively shallow calcite compensation depth (CCD) in the Eocene compared to the modern day, which has resulted in comparatively poor preservation of contemporaneous carbonate microfossils in deep-sea sediments, particularly in the Pacific Ocean (Lyle et al., 2005). Weak palaeomagnetic signals typical of carbonate-rich Palaeogene sediments are a further complication for the calibration of biostratigraphic datums. Therefore, typically, deep-sea sections with good microfossil preservation are characterized by poor magnetostratigraphies (e.g., Ocean Drilling Program, ODP Legs 143, 154, 198 and 208; Sager et al., 1993; Curry et al., 1995; Bralower et al., 2002; Zachos et al., 2004;), while those with good magnetostratigraphies suffer poor calcareous microfossil preservation (e.g., ODP Leg 199; Lyle et al., 2002). Similarly, in the classic land-based exposures in Italy (e.g., Gubbio) that constitute the magnetostratigraphic reference for a large part of the Eocene, calcareous microfossils are also typically poorly preserved and the magnetostratigraphy can be ambiguous (Lowrie et al., 1982; Napoleone et al., 1983; Jovane et al., 2007; Luciani et al., 2010).

One interval of Eocene time for which it has proven particularly problematic to obtain high quality sections (because of recovery difficulties), is the chron C18r/18n boundary and planktonic foraminiferal Zone E12 (Berggren and Pearson, 2005), the interval in which the MECO falls (Bohaty et al., 2009) (Fig. 1). Biozone E12 is defined by the total range of the short-lived tropical planktonic foraminiferal species

Orbulinoides beckmanni. *O. beckmanni* is a particularly useful biostratigraphic marker because, first, it divides what would otherwise be a long (~4 Myr) biozone, stretching from the highest occurrence (HO) of *Guembelitriodes nuttalli* at 42.3 Ma to the HO of *Morozovelloides crassatus* at 38.0 Ma, Zones E11-E13 (Berggren and Pearson, 2005) (Fig. 1). Second, the existing calibration for Zone E12 is coincident with the MECO (Fig. 1) (Sexton et al., 2006a; Bohaty et al., 2009), which raises the possibility that *O. beckmanni* might represent an 'excursion' taxon akin to those documented for the Paleocene-Eocene Thermal Maximum (Kelly et al., 1996, 1998). However, the relatively poor recovery of Zone E12 by deep-sea drilling has hindered direct calibration of this Zone to the geomagnetic polarity time-scale (GPTS). A near global hiatus near the chron C18r/C18n boundary at ~40.0 Ma truncates the top of planktonic foraminiferal Zone E12 in many deep-sea sequences (e.g., Karig et al., 1975; Erbacher et al., 2004), while other sequences are limited by the presence of chert or condensation horizons (Zachos et al., 2004), a lack of carbonate (Lyle et al., 2002), poor magnetostratigraphic control or the absence of the marker species *O. beckmanni* (e.g., Sager et al., 1993; Curry et al., 1995; Bralower et al., 2002; Zachos et al., 2004).

Here we present new high-resolution magnetic polarity data from Site 1051 alongside quantitative records of the biostratigraphic marker species *O. beckmanni* and benthic foraminiferal stable isotope records from ODP Site 1051 and, for comparison, similar records from Site 1260 in the Atlantic Ocean. ODP Site 1051 represents an ideal section to address the above stratigraphic issues because, on the basis of available records, it has a high sedimentation rate for a deep-sea site in the middle Eocene (~4 cm/kyr), it is stratigraphically continuous (at least to biozone and magnetochron level), it hosts sediments that are suited to develop a resolvable magnetostratigraphy and it is situated well above the local CCD, favouring preservation of calcareous microfossils (Shipboard Scientific Party, 1998). For comparison, ODP Site 1260 also benefits from a good magnetostratigraphy and carbonate microfossil preservation, but the sedimentary succession is truncated by a hiatus at the chron C18r/18n boundary (Shipboard Scientific Party, 2004; Suganuma and Ogg, 2006). These new datasets are used to: (1) improve the magnetostratigraphic resolution of the late middle Eocene interval at Site 1051, (2) refine the existing biomagnetostratigraphic calibrations at Sites 1051 and 1260, (3) assess the chronological reliability of the bioevents that define Zone E12 at Sites 1051 and 1260, (4) test whether the MECO is present in these tropical and northern hemisphere sites and (5) determine if the speciation or subsequent extinction of *O. beckmanni* are linked to the MECO.

2. Locations and geological setting

ODP Site 1051 (30°03’N; 76°21’W, modern water depth 1980 meters below sea level, mbsl) is situated on the Blake Nose plateau in the western North Atlantic Ocean (Fig. 2). The estimated palaeodepth for Site 1051 is 1000 - 2000 mbsl for the middle Eocene (Shipboard Scientific Party, 1998) with a palaeolatitude of ~25ºN (Ogg and Bardot, 2001). Site 1051 comprises a stratigraphically complete (at least to magnetochron level) expanded late Paleocene through middle Eocene sequence of siliceous nannofossil oozes interspersed with approximately 25 thin ash horizons (Shipboard Scientific Party, 1998). Estimated sedimentation rates are ~ 1 to 4 cm/kyr.

ODP Site 1260 (9°16’N; 54°33’W, modern water depth 2549 mbsl) (Fig. 2) was drilled on the Demerara Rise plateau (palaeowater depths for the Eocene close to those of the present day, Arthur and Natland, 1979) and was situated at a palaeolatitude of 1ºS in the middle Eocene (Suganuma and Ogg, 2006). Middle Eocene sediments at Site 1260 are primarily greenish grey nannofossil chalks with foraminifers and radiolarians (Shipboard Scientific Party, 2004), with average sedimentation rates across the focal interval of ~2 cm/kyr.

3. Methods

3.1 Palaeomagnetism

To generate a continuous high-resolution magnetic polarity record across Zone E12 at Site 1051, u-channel samples were taken following the shipboard composite depth section splice (Shipboard Scientific Party, 1998) between 66.15 and 146.63 meters composite depth (mcd). Below ~150 mcd, sediments were recovered using the extended core barrel, which makes them less suitable for detailed analysis.

All u-channel samples were measured on a 2-G Enterprises cryogenic magnetometer (at the National Oceanography Centre, Southampton) after progressive stepwise alternating field (AF) demagnetization at successive peak fields of 5, 10, 15, 20, 25, 30, 40, 50 and 60 milliTesla (mT), and occasionally up to 80 mT. The natural remanant magnetization (NRM) was measured at 1 cm stratigraphic intervals, although smoothing occurs because of the width of the magnetometer response function (half-width = 5 cm). Thus, data from the top and bottom 5 cm of each u-channel were excluded from this study because of edge effects (Roberts, 2006). The inclination and declination of the characteristic remanant magnetization (ChRM) was determined at 1 cm intervals using principal component analysis; with data from at least 4 demagnetization steps, and the quality of the linear regressions was estimated by calculating the maximum angular deviation associated with the best-fit line (Kirschvink, 1980). The age model for Site 1260 is based on Suganuma and Ogg (2006), which was supplemented by additional palaeomagnetic measurements by Edgar et al. (2007).

3.2 **Orbulinoides beckmanni** ***abundance counts***

To determine the LO and HO of *Orbulinoides beckmanni*, high-resolution relative abundance counts (percent of total planktonic foraminifera) were produced for sample splits of ~400 individuals from 482 samples at 10 cm sampling resolution (mean sampling interval of 3 kyr) for ODP Site 1051 and on 69 samples at ~30 cm sampling resolution (sampling interval 12 kyr) at ODP Site 1260. Samples were prepared for abundance counts by washing 20 cm^3 of bulk sediment over a 63 µm mesh and then dry sieved at 300 µm. Biozonations and taxonomy adopted for this study are those of Berggren and Pearson (2005), and Proto-Decima and Bolli (1970) and Premoli Silva et al. (2006), respectively. We distinguish *O. beckmanni* from its immediate ancestor *Globigerinatheka euganea* (see Plates I and II) by the presence of spiral sutural apertures between early chambers (Plate IIb,f and h) and more numerous (>4) smaller, sutural apertures in the last few chambers, e.g., Plate II, specimens a,e, i, j and l. An additional diagnostic criterion is the presence of small, circular apertures within the wall of the last few large chambers (areal apertures; see Plate II, specimens a, c, i, j and l), commonly found in *O. beckmanni* but never reported in any of the globigerinathekids (Premoli-Silva et al., 2006). Thus, when present, areal apertures are a useful diagnostic characteristic.

3.3 Oxygen and carbon isotope measurements

Benthic foraminiferal stable isotope ($\delta^{18}O$ and $\delta^{13}C$) data were generated using the species *Cibicidoides eoceanus* (Site 1260) and *Oridorsalis umbonatus* (Site 1051), following taxonomy employed by Tjalsma and Lohmann (1983) and van Morkhoven et al. (1986). Foraminifera were picked from the size range 250-350 µm and were cleaned by ultrasonication prior to isotopic analysis. Benthic foraminifera are relatively sparse at Site 1051 owing to dilution by siliceous microfossils. At Site 1260 benthic foraminifera are more abundant and sufficient individuals for stable isotope analysis (~3-5) were found in every sample examined. All stable isotope measurements were determined using a Europa GEO 20-20 mass spectrometer equipped with an automatic carbonate preparation system (CAPS). Results are reported relative to the Vienna Pee Dee Belemnite (VPDB) standard with an external analytical precision of 0.07‰ and 0.03‰ for $\delta^{18}O$ and $\delta^{13}C$, respectively. Stable isotope values generated from *Cibicidoides eoceanus* are adjusted to equilibrium by adding 0.28‰ VPDB to $\delta^{18}O$ values, following the Palaeogene correction factor for *Cibicidoides* (Katz et al., 2003) and 0.72‰ VPDB is added to the $\delta^{13}C$ values of *Oridorsalis umbonatus* to normalise to *Cibicidoides* (Katz et al., 2003).

4. RESULTS

4.1 Palaeomagnetic behavior and polarity zonation

U-channel samples from Site 1051 have comparatively weak magnetizations (~10^{-5} to 10^{-4} Am^{-1}), typical of carbonate-rich sediments, but with stable and readily interpreted palaeomagnetic behavior (Fig. 3a-f). Samples are characterized by a small, low-stability steeply dipping normal polarity component (Fig. 3a-f) that is interpreted to be as a drilling overprint. This magnetic overprint was successfully removed with peak AFs of <20 mT. The ChRM of the u-channel samples in the more strongly magnetized composite section (108 – 146 mcd; Fig. 4) was isolated between 20 and 50 mT and, toward the top of the composite section (~68 and 108 mcd), between the 5 and 25 mT demagnetization steps (because of the less stable demagnetization behavior in this upper interval, Fig. 3g and h). This is not ideal, and particular care was taken to discard data in this interval if there was a suggestion of an unremoved drilling overprint.

Magnetic polarity intervals were determined based on the clustering of positive or negative inclinations. Our new data from between 65 and 150 mcd provide a substantial improvement on the published lower-resolution dataset available between 0 and 150 mcd (Shipboard Scientific Party, 1998; Ogg and Bardot, 2001) (Fig. 4). Five distinct magnetozones (R1 to R3) are identified (Fig. 4), in our new dataset and the boundaries between these improved from a previous resolution of ±2.5 m (Ogg and Bardot, 2001) to between < 2 cm and ~ 1 m (Table 1).

Within each of the 'long' magnetozones investigated (N1 through N2) are a number of short-lived (~2-8 kyr) polarity intervals, e.g., at 128 and 130 mcd (Fig. 4). The majority of these short-lived polarity features are associated with large increases in the measured NRM intensity (Fig. 4) and are likely to reflect measurement artifacts resulting from large changes in NRM intensity (Roberts, 2006). These features might be attributable to dispersed ash particles that are coincident with at least several of the polarity events. One notable exception to this pattern occurs at 100 mcd (Fig. 4), which might represent an example of a short polarity interval associated with 'tiny wiggles' (e.g., Roberts and Lewin-Harris, 2000) that are observed in seafloor magnetic anomaly profiles within the late middle Eocene (Cande and Kent, 1992).

Regardless, the short-lived polarity intervals identified here are not considered in the overall polarity zonation.

4.2 Planktonic foraminiferal biostratigraphy

Planktonic foraminiferal assemblages at Sites 1051 and 1260 are typical of those found in (sub)tropical oceans in the late middle Eocene and are indicative of planktonic foraminiferal Zones E11 through E13. Microfossil preservation is good with planktonic foraminifera showing some evidence of recrystallization; specimens are ‘frosty’, not ‘glassy’ (Sexton et al., 2006b).

We have identified *Orbulinoides beckmanni* at both ODP sites (Table 2). *O. beckmanni* has some morphological variability within its range, with a shift to a more encompassing final chamber (increased test sphericity) and an increasing number of small supplementary sutural apertures at the base of the final chamber and between the earlier chambers (Plates I and II). This leads to highly distinctive forms toward the top of its stratigraphic range (Plate II). Of note, we find no stratigraphic significance in the presence or absence of areal apertures or ‘bulla-like’ structures.

The relative abundance of *O. beckmanni* within the total planktonic foraminiferal assemblage is shown in Figure 5a and b. Using our new magnetic stratigraphy for subtropical ODP Site 1051, we determine the LO of *O. beckmanni* to 40.5 Ma using the geomagnetic polarity time scale of Cande and Kent (1992, 1995; Fig. 5a), in the upper half of chron C18r (106.15 mcd). At equatorial Site 1260, the LO of *O. beckmanni* occurs toward the base of chron C18r (58.87 mcd) around a half million years earlier (41.0 Ma, Fig. 5b).

At both sites, for several hundred thousand years following its LO, *O. beckmanni* remains low in relative abundance (<2%, Fig. 5). At Site 1051, where a longer record is available, an abrupt increase (to ~4-6%) in the relative abundance of *O. beckmanni* occurs toward the base of chron C18n.2n at 40.1 Ma. Its relative abundance then remains on average at 3% for approximately 600 kyr, followed by a decrease and eventual extinction of *O. beckmanni* within chron C18n.1n at 61.90 mcd (at 39.5 Ma). We are unable to identify the HO of *O. beckmanni* at Site 1260 because the sedimentary succession is truncated by a hiatus at 36.1 mcd, which spans approximately five million years of geological time (middle-late Eocene) (Shipboard Scientific Party, 2004).

4.3 Stable isotope records

At both sites, benthic foraminiferal $\delta^{18}O$ records gradually shift by ~1‰ to lower values within chron C18r coincident with an overall shift to higher $\delta^{13}C$ values (Fig. 5c and d). The stable isotope record at Site 1260 is truncated by a hiatus at the top of chron C18r, but at Site 1051, benthic $\delta^{18}O$ values reach a short-lived (~40 kyr) minimum in the base of chron C18n.2n (at 40.05 Ma) coincident with an abrupt 1‰ decrease in $\delta^{13}C$ values (Fig. 5). Subsequently, both benthic $\delta^{18}O$ and $\delta^{13}C$ values at Site 1051 increase rapidly, followed by a more gradual shift to overall higher values. There is good agreement between the amplitude and timing of the $\delta^{18}O$ shift in the bulk (Bohaty et al., 2009) and benthic $\delta^{18}O$ records (this study) at Site 1051. At Site 1260, superimposed on the longer-term patterns of stable isotope change are a number of discrete negative $\delta^{13}C$ excursions (~1‰) with a duration of ~40 kyr each at 40.3, 40.4, 41.2 and 41.4 Ma (Fig. 5d). The two oldest of these four excursions, occur prior to the onset of the MECO and are not associated with any obvious lithological changes (Shipboard Scientific Party, 2004). In contrast, the younger $\delta^{13}C$ excursions at 40.3 and 40.4 Ma, superimposed on the shift to more positive $\delta^{13}C$ values during the MECO are coincident with thin (1-2 cm thick) clay horizons (cf. the C19r event already documented at Site 1260, Edgar et al. 2007). None of these $\delta^{13}C$ excursions are readily discernible in the lower-resolution benthic $\delta^{13}C$ record of Site 1051 (Fig. 5d).

5. **Discussion**

5.1 Correlation to the Geomagnetic Polarity Time Scale

We integrate our new magnetic polarity pattern with published datasets (Shipboard Scientific Party, 1998; Ogg and Bardot, 2001) between 0 and 150 mcd identifying nine distinct magnetozones (R1-N4; Fig. 6). The resulting polarity patterns provides a correlation with the GPTS between chrons C19r and C17r (Fig. 6). From 150 to 90 mcd our interpretation is in good agreement with published records (Shipboard Scientific Party, 1998; Ogg and Bardot, 2001). However, above 90 mcd our interpretation differs from that of the Shipboard Scientific Party (1998) and Ogg and Bardot (2001) significantly, resulting in a two million year offset (Fig. 6). This discrepancy arises from our differentiation of chron C18 into subchrons C18n.2n, C18n.1r and C18n.1n, leading to the re-assignment of magnetozone N2 to chron C18n.2n, and of subsequent chrons, e.g., magnetozone R3 = chron C18n.1r, N3 = chron C18n.1n, R4 = chron C17r and N4 = chron C17n. Chron C18n was not differentiated in the earlier polarity scheme because interpretation of the polarity pattern based on calcareous nannofossil datums suggested that C18n was very condensed at this site (Fig. 6, Shipboard Scientific Party, 1998; Ogg and Bardot, 2001). Resulting sedimentation rates for Site 1051 are relatively uniform (~4 cm/kyr) and are consistent with planktonic foraminiferal and radiolarian datums (Fig. 6). However, existing age calibrations for the respective HO and LO of calcareous nannofossil taxa *Dictyococcites bisectus* and *Chiasmolithus oamaruensis* are offset by almost one million years from the new age model (Fig. 6) and indicate the need for further calibration of biostratigraphic datums to the GPTS.

5.2 Revised calibrations for the lowest and highest occurrence of Orbulinoides beckmanni

At Site 1051, high sedimentation rates, good magnetostratigraphic control and high-resolution sampling allow us to directly calibrate the LO and HO of *Orbulinoides beckmanni* to the GPTS. Using our new age model for Site 1051, and the published refined magnetic stratigraphy from Site 1260 (Suganuma and Ogg, 2006; Edgar et al., 2007), a 500 kyr offset is evident in the position of the LO of *O. beckmanni* between Sites 1051 and 1260 (Fig. 5a and b). While the LO of *O. beckmanni* at Site 1051 in chron C18r (40.5 Ma) is consistent with that indicated by Berggren et al. (1995), at Site 1260 it is earlier (at the base of chron C18r at 41.0 Ma). The diachroneity reported here exceeds the uncertainties that are reasonably attributable to methodological (±<13 kyr) or age model inconsistencies (±<38 kyr) and is therefore interpreted to represent genuine geological diachrony between the two Atlantic Ocean sites of ~500 kyr. Consistent with the latitudinal diachrony observed between 2°S (Site 1260) and 25°N (Site 1051) is the later LO of *O. beckmanni* reported at 40.2±0.04 Ma (in the top part of chron C18r) at ~40°N in the Contessa Highway section, Italy (Jovane et al., 2007) (Fig 2). Recognition of the regionally diachronous LO of *O. beckmanni* has probably gone undetected previously because of the lack of sections available on which the LO and HO can be tied directly to the GPTS.

Of note, the HO of *O. beckmanni* recorded here at Site 1051 in magnetochron C18n.1n is much later (600 kyr) than that reported in a recent calibration of its HO to 40.0 Ma in chron C18n.2n at ODP Site 1052 (Wade, 2004). This discrepancy is most likely attributable to the equivocal recognition and subdivision of chron C18n at Site 1052 (Ogg and Bardot, 2001), and is further complicated by the proposal of a 600 kyr-long hiatus (Pälike et al., 2001). Because the LO and HO of *O. beckmanii* defines the upper and lower boundaries of planktonic foraminiferal Zone E12, this zone at Site 1051 is at least 400 kyr longer than existing calibrations (Berggren and Pearson, 2005).

5.3 *Environmental controls on* Orbulinoides beckmanni's *biogeography*

We invoke an environmental control on the biogeography of *O. beckmanni* to explain the observed diachroneity in its lowest occurrence and its short total range duration. Expansion of species ranges from the tropics to higher latitudes is a common source of diachrony in first appearances of marine plankton (Kennett, 1970; Moore et al., 1993; Raffi et al., 1993; Spencer-Cervato et al., 1994; Kucera and Kennett, 2000; Sexton and Norris, 2008). Although little is known about the palaeoecology of *O. beckmanni*, this species is restricted to tropical and warm mid-latitudes (Bolli et al., 1972; Premoli Silva et al., 2006;) between ~30ºS and 45ºN, highlighted in our compilation of geographic occurrence (Fig. 2), suggesting that sea surface temperature (SST) may have played a major role in its geographic distribution. As surface waters warmed during the MECO (Bohaty and Zachos, 2003; Bohaty et al., 2009), conditions may have become more favorable for this taxon at higher latitudes thereby allowing geographic range expansion to ~45°N (Fig. 2).

The HO of *O. beckmanni* post-dates the MECO at Site 1051 by at least 600 kyr (Fig. 5) which indicates that the apparent abrupt cooling at the termination of the MECO was not sufficient to completely eliminate this species from Site 1051. However, SST continued to decrease (Bohaty et al., 2009) and may have fallen below a critical threshold necessary to sustain viable population numbers. Despite the undoubted diagenetic overprint on the bulk sediment record, $\delta^{18}O$ values at the LO and HO of *O. beckmanni* are similar (~0.7‰, Fig. 5c), which is compatible with a thermal threshold controlling *O. beckmanni's* distribution. This also raises the possibility that the HO of *O. beckmanni* may be latitudinally diachronous. This interpretation is in keeping with the earlier HO of *O. beckmanni* (39.9 Ma, base of chron C18n.2n) at 40°N in the Contessa section (Jovane et al., 2007; Fig. 2). *O. beckmanni* is not confined to the MECO event and thus, by definition, this species cannot be termed an 'excursion taxon'. Nevertheless, the relatively short range of *O. beckmanni* (<1 Myr), combined with the coincidence of its peak abundance with peak ocean warmth, implies that this taxon had a narrow environmental tolerance and/or the ecological niche that it occupied disappeared because of cooling surface waters (Fig. 5c).

5.4 Constraints on the timing and environmental impact of the MECO

Our correlation of the magnetostratigraphic records to the GPTS suggests that the transient $\delta^{18}O$ and $\delta^{13}C$ shifts observed across the chron C18r/18n boundary at Sites 1260 and 1051 (Fig. 5c and d) are low latitude representations of the MECO. These are the first detailed records from the (sub)tropics and demonstrate that the MECO is a truly global event. The magnitude, relative timing and pattern of stable isotope change are consistent with published benthic foraminiferal (e.g., ODP Site 748, Fig. 5c; Bohaty and Zachos, 2009) and bulk sediment (Jovane et al., 2007; Bohaty et al., 2009; Spofforth et al., 2010) stable isotope records from other ocean basins, which implies that the gradual onset and abrupt $\delta^{18}O$ maximum are reliable for global stratigraphic correlation (Fig. 5c and d).

At present it is unclear whether the higher-resolution features, notably, the two $\delta^{13}C$ excursions preceding the MECO peak at Site 1260, are also global in character. Because these excursions are coincident with clay layers which imply carbonate dissolution, they are reminiscent of simultaneous transient CCD shoaling and negative isotopic shifts associated with small inferred 'hyperthermal' events reported in other parts of the Eocene (e.g., Lourens et al., 2005; Edgar et al., 2007; Quillévéré et al., 2008). If these excursions prove to be present in other deep-sea sites, they may help to shed light on the mechanisms driving warming during the MECO.

6. Conclusions

We present new stable isotopic, magnetostratigraphic, and biostratigraphic records from (sub)tropical Atlantic ODP Sites 1051 and 1260 for the late middle Eocene, spanning the MECO. These represent the first detailed records of the MECO from the tropics and subtropics and demonstrate that the event is truly global. Closely associated with the MECO is the range and abundance variations of the biostratigraphically important planktonic foraminiferal species *O. beckmanni*. Detailed abundance counts of this species reveal a latitudinal diachrony of ~500 kyrs in its lowest occurrence, observed 500 kyrs earlier in the tropics (41.0 Ma at Site 1260) than in the subtropics (40.5 Ma at Site 1051). This latitudinal diachrony is attributed to the poleward expansion of warm surface waters during the onset of the MECO, which created favorable conditions at extra-tropical latitudes for this thermophyllic species. Using our high-resolution magnetic polarity record at ODP Site 1051, the diachronous FO of *O. beckmanni* occurs within chron C18r and its disappearance within chron C18n.1n at 39.5 Ma, 600 kyr younger than previously reported. The disappearance of *O. beckmanni* from the subtropics is likely related to progressive cooling of sea surface waters below some critical threshold rather than to abrupt environmental change.

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Figure captions

Figure 1 – Study interval in the context of Cenozoic climate trends. a) Cenozoic benthic foraminiferal $\delta^{18}O$ record modified from Zachos et al. (2008). The MECO is shown on a revised age scale in keeping with this study. b) The Geomagnetic polarity time scale used follows Cande and Kent (1992; 1995). New 'E' planktonic foraminiferal tropical biozonation scheme from Berggren and Pearson (2005), and 'P' tropical biozonation scheme from Berggren et al. (1995). c) Benthic foraminiferal $\delta^{18}O$ record from Site 748, Southern Ocean (Bohaty et al., 2009). Black vertical line represents the duration of the MECO based on the $\delta^{18}O$ stable isotope pattern. Black dashed lines denote the position of the MECO relative to the GPTS and tropical zonation scheme. Grey boxes denote the study interval and the black vertical line represents the duration of the MECO based on the $\delta^{18}O$ pattern.

Figure 2 – Palaeogeographic reconstruction of the Eocene illustrating the presence and absence of *Orbulinoides beckmanni*. ODP Sites 1051 and 1260 (stars) used in this study. Solid circles indicate the presence and open circles the absence of *O. beckmanni*. Data are compiled from deep-sea drill sites and exposed marine sections that coincide with planktonic foraminiferal Zone E12 but are not necessarily stratigraphically 'complete' sections. Data are compiled from Lowrie et al. (1982), BouDagher-Fadel and Clark (2006), Pearson et al. (2006), Babic et al. (2007), Jovane et al. (2007) and http://www-odp.tamu.edu/database/. To prevent bias, sites where *O. beckmanni* is absent because of hiatuses, dissolution, lack of carbonate or non-recovery of this stratigraphic interval are excluded. The base map for 40 Ma was

generated from www.odsn.de/odsn/series/palaeomap/palaeomap.html.

Figure 3 – Typical AF (alternating field) demagnetization behavior of sediments from ODP Site 1051. a-f) samples with stable demagnetization behaviour. g-h) samples with less-stable demagnetization behaviour. In the vector component diagrams, open symbols represent projections onto the vertical plane and closed onto the horizontal plane. Jmax is the NRM value measured during AF demagnetization.

Figure 4 – Down-core variations in the intensity of the natural remanent magnetization (NRM) and inclination for ODP Site 1051. a) Inclination data from Ogg and Bardot (2001). Closed symbols represent data points with maximum angular deviation (MAD) values of <10º, while open data points have MAD values between 10º and 15º. b) MAD values of data shown in panels c and d. c) NRM intensity after AF demagnetization at 25 mT for samples shown in panel c. d) Inclination data for the shipboard composite depth sections (mcd – meters composite depth). Grey symbols = data from Hole A and black symbols from Hole B, with MAD values of <10º (this study). Horizontal dashed lines represent splice points. The magnetic polarity zonation is shown on the right. Black represents normal and white represents reversed polarity intervals.

Figure 5 – Stable isotope records across the middle Eocene climatic optimum and relative abundance records of *O. beckmanni*. Relative abundance records of *O. beckmanni* at ODP Sites 1051 (panel a) and 1260 (panel b). Horizontal black lines denote core depths between which the lowest and highest occurrences (LO and HO) of *O. beckmanni* were recorded by the Shipboard Scientific Parties (1998; 2004).

Revised planktonic foraminiferal zone boundaries based on this study shown. Arrows indicate new placement of the boundaries of Zone E12. c) Benthic foraminiferal $\delta^{18}O$ records from Sites 1051 and 1260 (this study). Starred (*) records are from Bohaty et al. (2009) and are aligned on the new Site 1051 age model. d) Benthic foraminiferal $\delta^{13}C$ records from Sites 1051 and 1260 (this study). Starred (*) records are from Bohaty et al. (2009) and are aligned on the new Site 1051 age model.

Figure 6 - Age versus depth plot with correlation of the ODP Site 1051 polarity zonation to the geomagnetic polarity time scale of Cande and Kent (1992, 1995). Calcareous plankton and radiolarian datums determined by the Shipboard Scientific Party (1998) are shown by colored diamonds (errors indicated by vertical black lines). Ages are from Berggren et al. (1995), with the exception of the highest occurrence (HO) of *O. beckmanni* and the extinction of *Morozovelloides* and large acarininids, which are from Wade (2004). Revised placement of the LO and HO of *O. beckmanni* are shown by solid circles. Polarity intervals marked ‘R’ have reversed polarity and those marked ‘N’ have normal polarity. mcd = metres composite depth. The grey line represents the age model from SSP’98 = Shipboard Scientific Party (1998) and O&B’01 = Ogg and Bardot (2001).

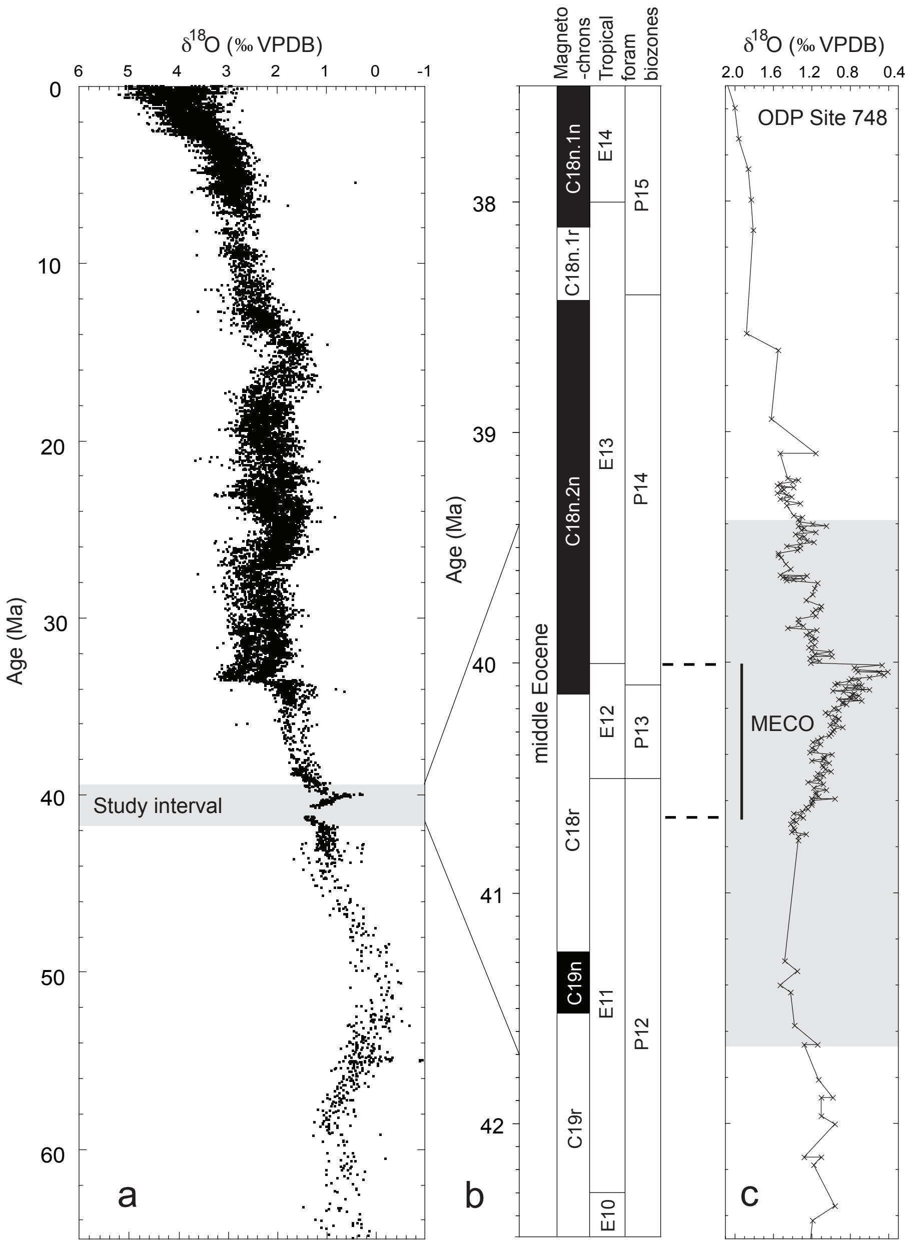
Plate I - Scanning electron microscope images from ODP Site 1051 that illustrate morphological development within the clade leading to *Orbulinoides beckmanni*. Scale bars are 100 µm. (a) *Subbotina senni*, Sample 1051B 7H-5, 65-66 cm. (b) *Globigerinatheka subconglobata*, Sample 1051B 9H-5, 35-37 cm. (c) *Globigerinatheka barri*, Sample 1051B 9H-5, 35-37 cm. (d) *Globigerinatheka kugleri*, Sample 1051B 11H-2, 65-67 cm. (e) *Globigerinatheka curryi*, Sample 1051B

11H-3, 131-133 cm. (f) *Globigerinatheka mexicana*, Sample 1051B-11H-4, 65-67 cm. (g) *Globigerinatheka euganea*, Sample 1260A 6R-1, 7-8.5 cm. (h) *Globigerinatheka euganea*, Sample 1051B 11H-3, 145-147 cm. (i) *Orbulinoides beckmanni*, Sample 1051B 11H-3, 131-133 cm. (j) .*Orbulinoides beckmanni*, Sample 1051B 9H-5, 35-37 cm. (k) *Orbulinoides beckmanni*, Sample 1051B 11H-3, 131-133 cm. (l) *Orbulinoides beckmanni*, Sample 1051B 9H-5, 5-7 cm.

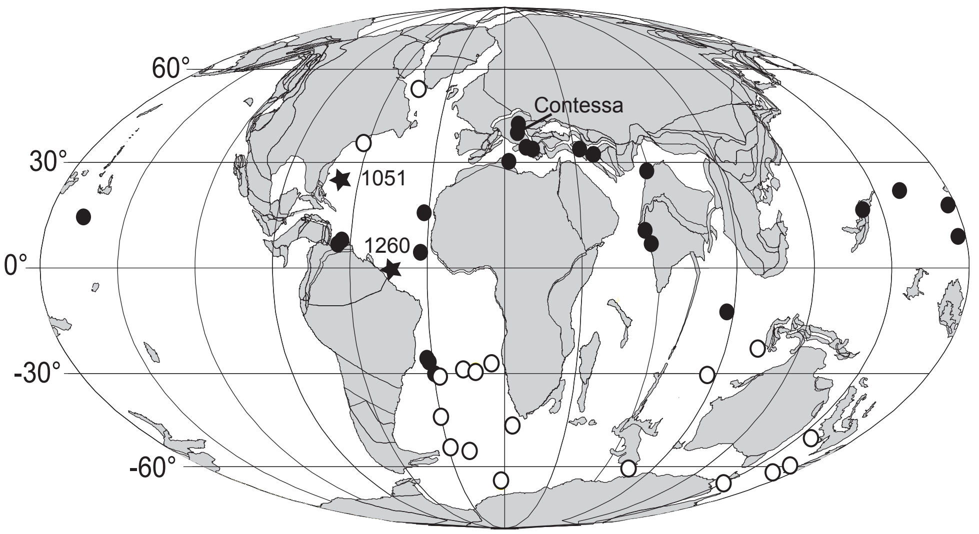
Plate II - Scanning electron microscope images from ODP Sites 1051 and 1260 that illustrate morphological variability within *Orbulinoides beckmanni*. Scale bars are 100 µm. (a) *Orbulinoides beckmanni*, Sample 1051B 8H-2, 105-107 cm. (b) *Orbulinoides beckmanni*, Sample 1051B 8H-2, 105-107 cm. (c) *Orbulinoides beckmanni*, Sample 1051B 8H-2, 105-107 cm. (d) *Orbulinoides beckmanni*, Sample 1051A 8H-4, 45-47 cm. (e) *Orbulinoides beckmanni*, Sample 1051A 8H-4, 45-47 cm. (f) *Orbulinoides beckmanni*, Sample 1051A 8H-4, 45-47 cm. (g) *Orbulinoides beckmanni*, Sample 1051A 8H-6, 5-7 cm. (h) *Orbulinoides beckmanni*, Sample 1051A 8H-6, 5-7 cm. (i) *Orbulinoides beckmanni*, Sample 1051A 8H-6, 5-7 cm. (j) *Orbulinoides beckmanni*, Sample 1260A 6R-1, 7-8.5 cm. (k) *Orbulinoides beckmanni*, 1260A 6R-1, 7-8.5 cm. (l) *Orbulinoides beckmanni*, Sample 1260A 6R-1, 7-8.5 cm.

Table 1 – Polarity zones and interpretation of chrons for ODP Site 1051.

Table 2 – Comparison of magnetobiochronology of planktonic foraminiferal datum events identified by Berggren et al. (1995), *Wade (2004), and this study.

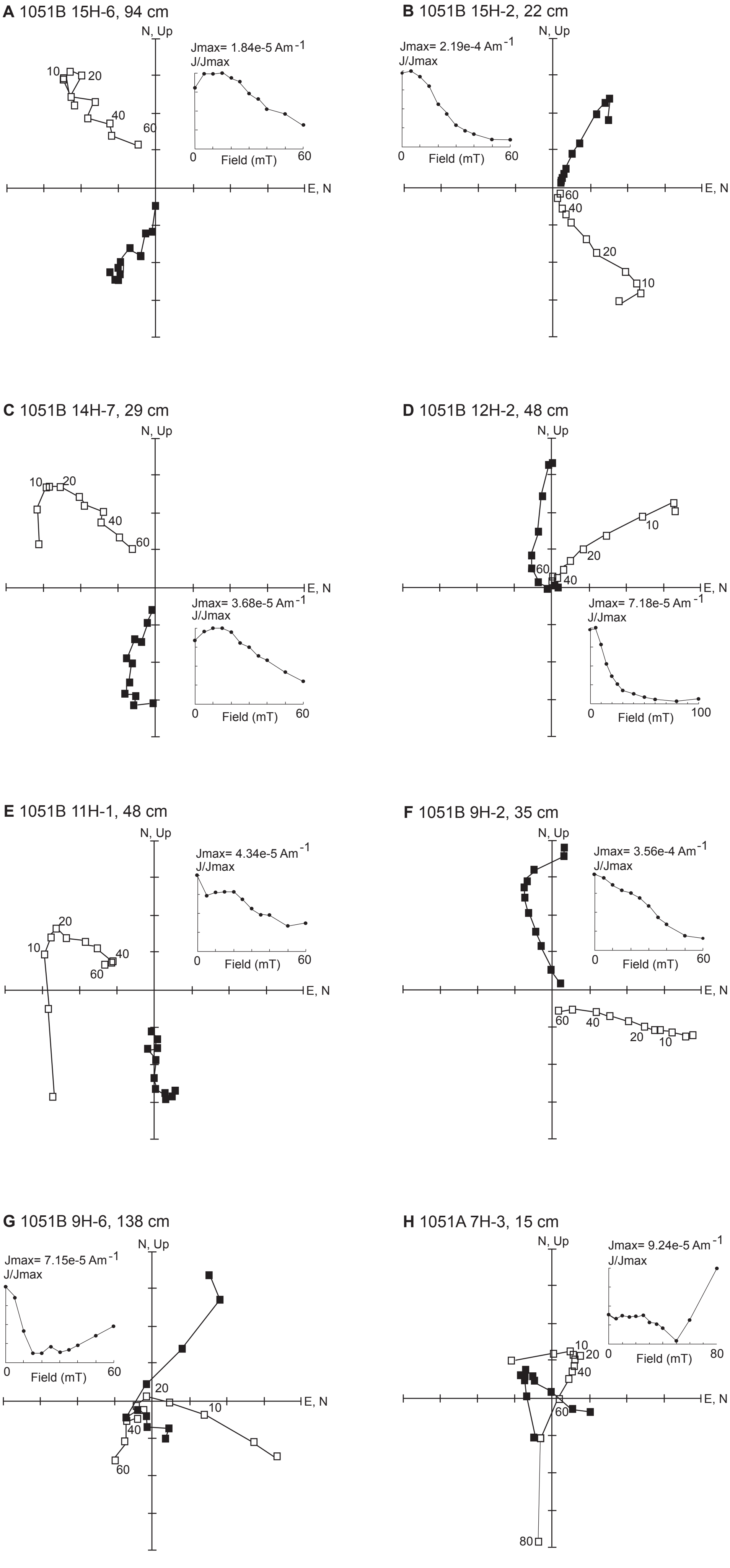


Edgar_Figure 1



● *O. beckmanni* present
○ *O. beckmanni* absent

Edgar_Figure 2



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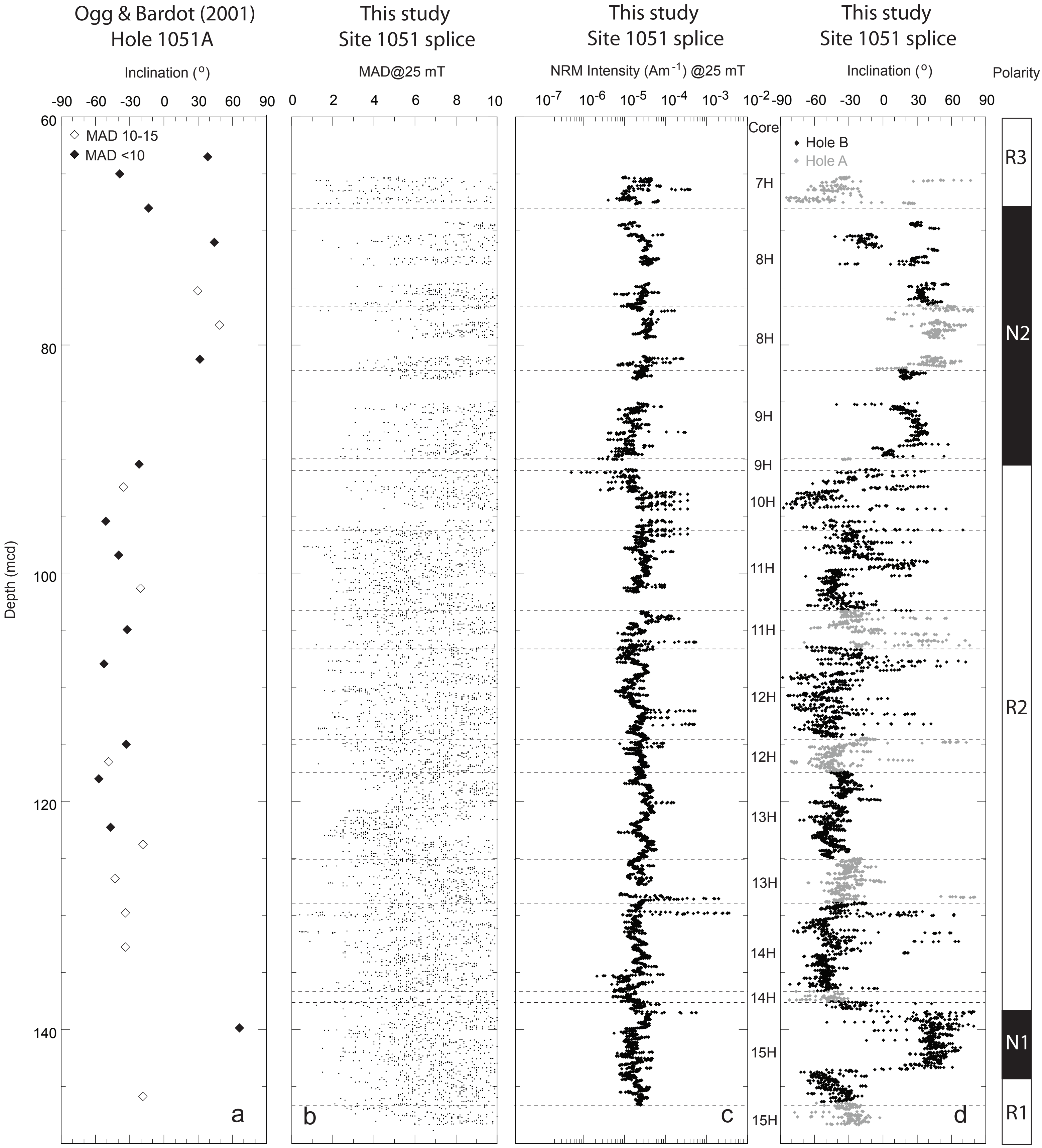

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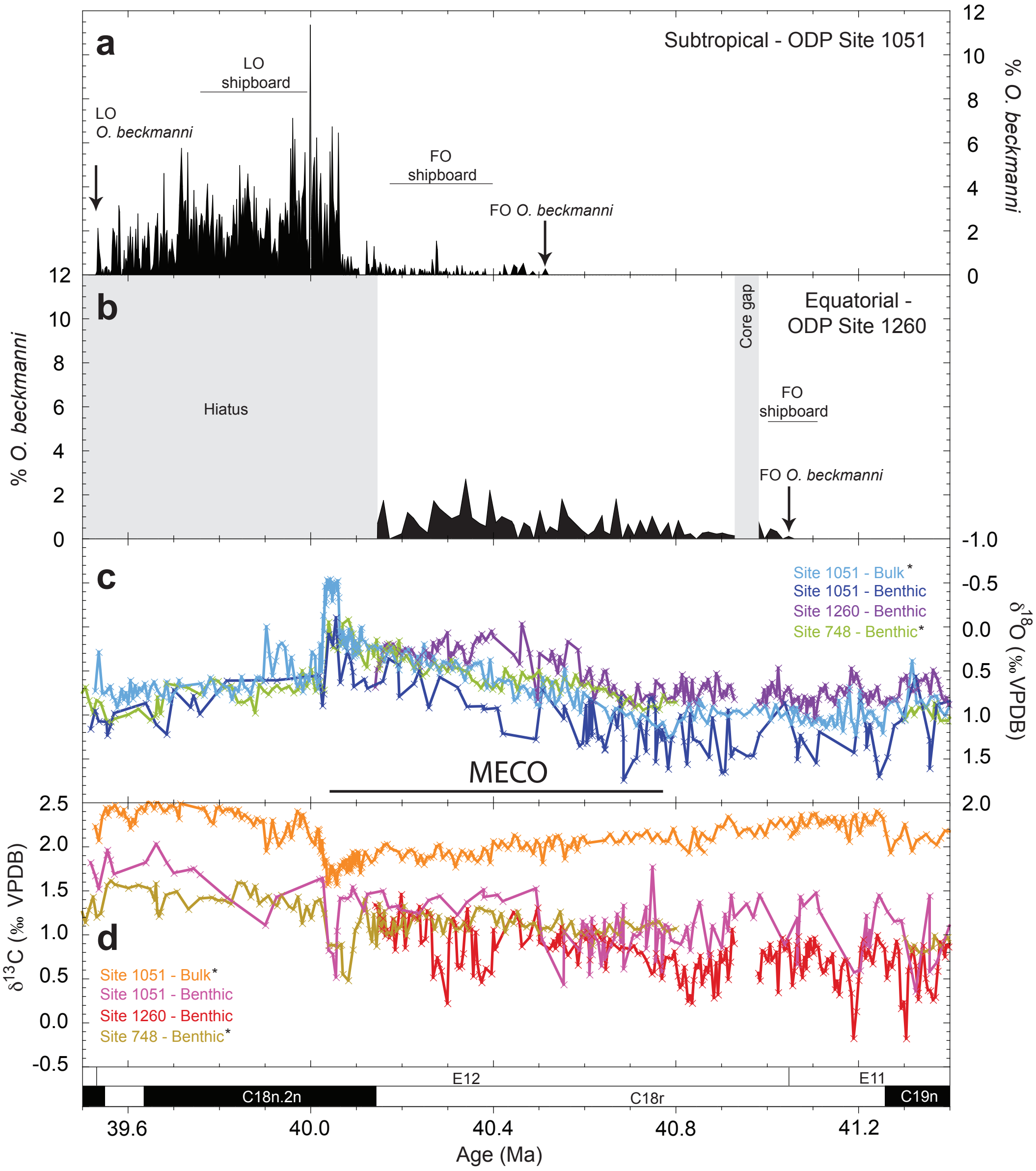

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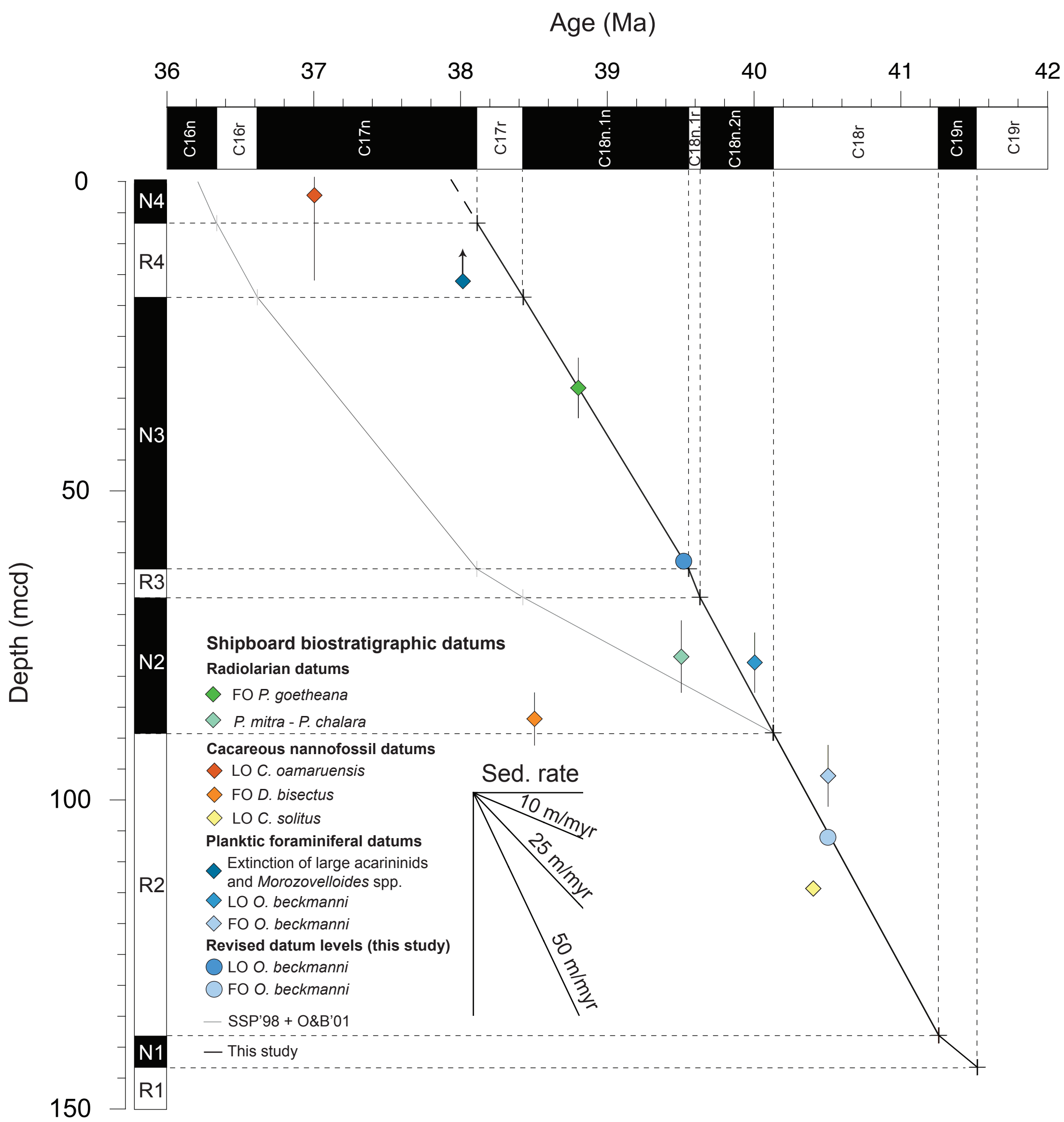

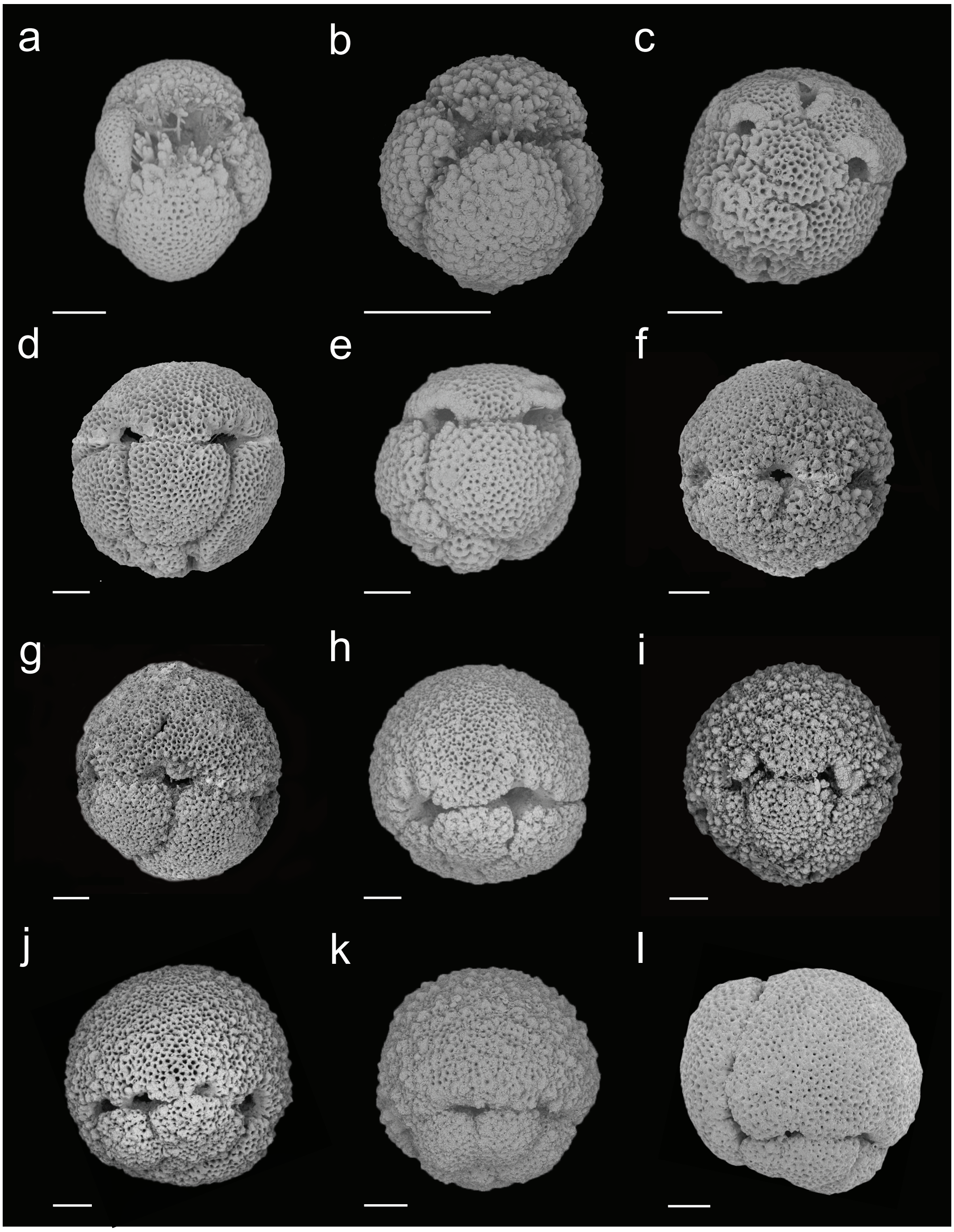

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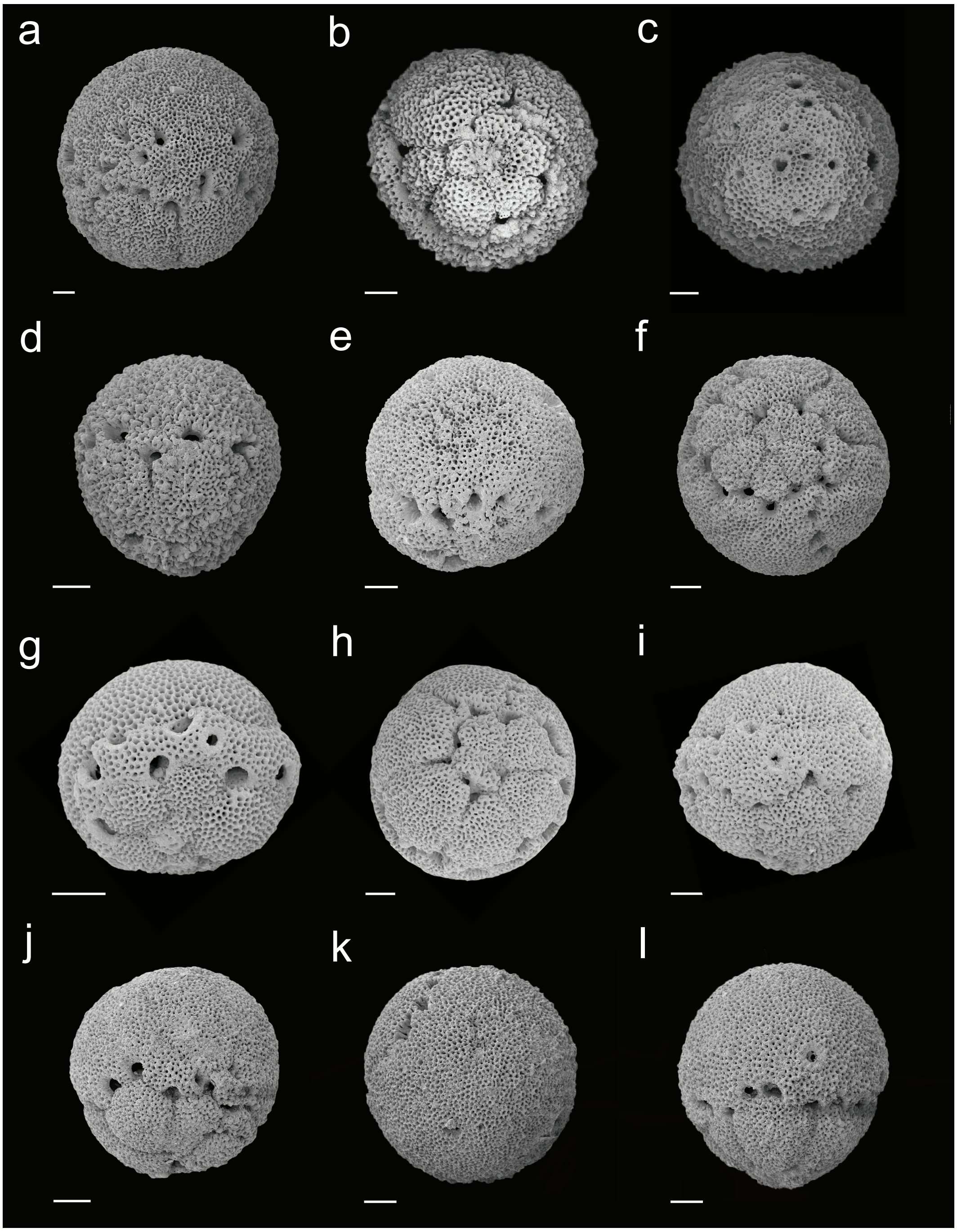

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Table 1

Polarity zone	Chron (base)	OB&'01 T (mcd)	OB&'01 B (mcd)	This study T (mcd)	This study B (mcd)	Age CK95 (Ma)
-	C16n	7.00*	-	-	-	36.410
-	C16r	19.00*	-	-	-	36.618
N4	C17n	60.35	65.00	7.00*	-	38.113
R4	C17r	68.00	71.00	19.00*	-	38.426
N3	C18n.1n	-	-	60.35	65.00	39.552
R3	C18n.1r	-	-	67.52	67.54	39.631
N2	C18n.2n	-	-	88.90	90.00	40.130
R2	C18r	135.78	139.88	138.41	138.43	41.257
N1	C19n	142.88	145.88	143.52	143.54	41.521

Magnetochron ages from Cande and Kent (1992, 1995) referred to as CK95. N = normal, R = reverse, T = top, B= base and mcd = meters composite depth. * = magnetochron boundaries from the Shipboard Scientific Party (1998). OB&'01data from Ogg and Bardot (2001).

Datum	Shipboard study T (mcd)	B (mcd)	Age CK95 (Ma)	Age GPTS04 (Ma)	This study T (mcd)	B (mcd)	New Age CK95 (Ma)	Age GPTS04 (Ma)
ODP Site 1051								
HO *O. beckmanni*	73.26	82.95	40.0*	39.4	61.80	61.90	39.5	39.0
LO *O. beckmanni*	91.45	101.35	40.5	39.8	106.15	106.45	40.5	39.8
ODP Site 1260								
LO *O. beckmanni*	57.80	59.30	40.5	39.8	58.87	59.17	41.0	40.4

Geomagnetic polarity time scales of Cande and Kent (1992, 1995) = CK95 and Gradstein et al., 2004 = GPTS04. LO and HO are lowest and highest occurrences, T = top and B = base, mcd = metres composite depth and * = Wade (2004).