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Planktonic foraminifera biostratigraphy and assemblage analysis
across the Eocene/Oligocene boundary at IODP Site U1411,
Newfoundland Margin

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Abstract

The Eocene-Oligocene transition (EOT) saw the development of large continental glaciers on Antarctica as well as restructuring of the global oceans. Along with the physical changes major evolutionary turnover in several marine plankton groups occurred. However, the nature of the turnover and its relation to global climate change across latitudes, especially in the North Atlantic, has remained uncertain. Therefore, utilizing drill cores from IODP Exp. 342 Site U1411, this study produced planktonic foraminifera assemblage records to investigate biotic turnover in a high-northern latitude setting exposed to Eocene-Oligocene climate change. The assemblages are dominated by small opportunistic surface dwellers and sub-thermocline species through the studied section (33.5-35.1 Ma), but supports both a large high-latitude planktonic foraminifera community and a small tropical community. Major planktonic foraminifera turnover events does not coincide with shifts in stable isotopes indicative of global cooling and ice growth, but instead are focused in two separate phases of turnover and extinction; the first between 34.3-34.7 Ma, and the second over a ~500 kyr window focused at E/O boundary. This is consistent with results from planktonic foraminifera from Tanzania and other fossil groups globally. Overall diversity changed less at Site U1411 than in the tropics during the EOT, probably because the most common species already had some degree of cold adaptation or preference for variable conditions. Grouping of species into surface, thermocline and sub-thermocline ‘eco-groups’ revealed that the upper ocean pelagic habitats suffered equal environmental stress and evolutionary turnover. Changes become more visible when individual taxa are studied within eco-groups: e. g. among thermocline dwellers, species of *Subbotina* switch out with incoming species of *Dentoglobigerina*. This reveals changes and evolutionary pressures within the thermocline without net loss of thermocline dwellers. Small opportunistic surface taxa seem to display the strongest variability, and the results suggest that the variability may have an orbital influence which likely caused changes in stratification controlled mixing and food supply.

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1. Introduction

The Eocene-Oligocene transition (EOT) is arguably the most prominent climate transition of the entire Cenozoic. It marks the end of an extended period of greenhouse climate and the onset of a cooler glacial climate mode with large continental glaciers forming on Antarctica for the first time (Zachos et al., 1996, 2001). Existing records indicate the transition was rapid and occurred over 500kyr in two 40kyr long steps, which are most clearly recognised in deep sea cores as increases in benthic foraminifera $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ (Coxall et al., 2005). The first $\delta^{18}\text{O}$ increase (EOT-1) has been attributed to global cooling (Katz et al., 2008; Lear et al., 2008; Wade et al., 2012), which resulted in deep sea cooling as high latitude deep water source regions cooled, while the second step (Oi-1) is thought to have been primarily caused by increases in seawater $\delta^{18}\text{O}$ due to the rapid expansion of the Antarctic ice sheets (Lear et al., 2008). The cooling was most pronounced in polar regions which resulted in strengthening of latitudinal temperature gradients. At the same time, fossil records reveal major disruption to Earth's terrestrial and marine ecosystems (Coxall and Pearson, 2007 for a review), indicating strong evolutionary forcing as many species had to adapt to the colder, and on land, more arid climate.

The glaciation itself was most likely caused by global drawdown of $p\text{CO}_2$ (Pearson et al., 2009; Pagani et al., 2011) accompanied by an optimal orbital configuration which promoted cool summers (Coxall et al., 2005), as the CO_2 threshold for Antarctic glaciation was reached (Deconto et al., 2008). Direct evidence for the glaciation is found close to Antarctica where ice rafted debris appears in the sedimentary record at the same time as the global stable isotope shift in benthic foraminifera (Zachos et al., 1992). The estimated size of the early Oligocene ice sheet based on foraminiferal Mg/Ca records show that it was probably roughly the same size as the present day ice sheets or larger (Katz et al., 2008). Because of this the development of the Antarctic ice sheet caused a significant drop in global sea-level which shifted carbonate production from the shelves to the deep-ocean, deepening the CCD by 1 km, significantly altering the carbonate chemistry of the global oceans (Coxall et al., 2005).

2. Previous Research and Specific Aims

A growing number of detailed microplankton and geochemical studies across the EOT indicate that evolutionary turnover in pelagic ecosystems occurred due to changes in ocean structure, circulation and nutrient availability (Dunkley Jones et al., 2008; Wade and Pearson, 2008; Cotton and Pearson, 2011; Egan et al., 2013). However, so far the focus has been on the

Southern Ocean and Indo-Pacific (Pearson et al., 2008; Wade and Pearson, 2008; Egan et al., 2013; Villa et al., 2014), implying major changes in southern hemisphere circulation, but very little is known about the planktonic foraminifera turnover in the northern hemisphere, particularly the North Atlantic for which proxy data coverage is also sparse. Existing planktonic foraminifera studies from discontinuous Atlantic cores drilled in the 1970's and 80's suggests parallel plankton changes among North Atlantic planktonic foraminifera (Berggren, 1972; Boersma, 1986; Boersma and Premoli Silva, 1986; Coccioni et al., 1988; Premoli Silva and Boersma, 1989) however, the resolution and core quality is insufficient to untangle climate related cause and effect relationships. Moreover, planktonic foraminifera taxonomic frameworks have changed markedly in the past 40 years making taxon range data comparisons impossible.

Therefore, this study utilized newly recovered material from IODP Site U1411 drilled on the Southeast Newfoundland Margin with excellent microfossil preservation (Norris et al 2014), along with an up to date taxonomy of late Eocene to Oligocene planktonic foraminifera (Wade et al., in review) to investigate the North Atlantic pelagic ecosystem response to EOT climate change. This was done by producing high-resolution records of planktonic foraminifera assemblages across the EOT along with a detailed biostratigraphy. The analysis involves grouping the recognized species into 'ecological groups' (eco-groups) defined previously using multispecies carbon and oxygen stable isotope analysis (Pearson et al., 2006; Wade and Pearson, 2008; Aze et al., 2011). The data are compared to Site U1411 bulk CaCO₃ records of oxygen and carbon stable isotopes (Bohaty et al., in prep.) to assess the relationship between the observed evolutionary turnovers and major climate change events of the EOT. The new observations from Site U1411 are then compared to a similar data set from the tropical Indian Ocean (Wade et al., 2008) to test the hypothesis that *the North Atlantic experienced similar changes in planktonic foraminifera evolution as has been observed in other ocean basins in terms of changes in assemblage makeup and community structure*. An important aspect of this study is that I have attempted to incorporate the contribution of the small taxa, which has been largely overlooked in the past (e. g. Wade and Pearson, 2008), but that may hold important clues as to the controls on planktonic foraminifera assemblage variability in this mid latitude NA setting.

Therefore, the specific aims of this thesis has been to:

- Define the stratigraphic distribution of planktonic foraminifera at IODP Site U1411.
- Test taxonomic concepts presented in the ‘Atlas of Oligocene Planktonic Foraminifera’ (Wade et al., in prep.) at this high latitude North Atlantic setting.
- Establish the biostratigraphic range of *Hantkenina* and other important planktonic foraminifera taxa in the EOT sequence at Site U1411. Specifically, determine the relationship of this and other extinctions to the pattern of bulk CaCO₃ isotopes change at this site.
- Determine patterns of assemblage variability, diversity and community structure using ecological/diversity statistical indices and relative abundance fluctuations of the planktonic foraminifera assemblage at Site U1411.
- Compare Site U1411 results to other EOT sequences from other ocean basins with similar data and interpret the results in relation to existing understanding of EOT climate change and changes observed in planktonic foraminifera and other planktonic biota.

3. Background

3.1 *Planktonic foraminifera*

Planktonic foraminifera are a group of single celled marine zooplankton that float freely in the water column. Their most distinguishing characteristic is the production of a calcium carbonate test that hosts the cytoplasm of the single cell that makes up the organism (Hemleben et al., 1989). To feed planktonic foraminifera extend a filamentous structure known as the pseudopodial network, which captures a variety of different prey/food items ranging from other protistan planktonic organisms (including phytoplankton and zoo plankton) to small arthropods (Aze et al., 2011). The highest concentration of species and individuals are found in the photic zone (Hemleben et al., 1989). Other species live closer to the base of the mixed layer or within the thermocline while others are recorded to have habitat preferences extending up to a thousand of meters down in the water column. These deep dwelling species likely feed on detritus sinking from the upper parts of the ocean (Hemleben et al., 1989).

Modern planktonic foraminifera communities are diverse with 46 different species identified (Aze et al., 2011). Species are widely distributed in the world's ocean with varying diversity depending on living environment (Rutherford et al., 1999). Recent studies of marine biodiversity have identified that planktonic foraminifera communities are most diverse at the equator with peaks in diversity also occurring between 20-40° N and S, which corresponds with the sub-tropical gyre systems (Rutherford et al., 1999). This is, in fact, a pattern that can be observed in many marine organisms today, ranging from protozoa to invertebrates (Tittensor et al., 2010).

When planktonic foraminifera die their tests sink to the seafloor where they can accumulate continuously in the sedimentary record. If conditions are favourable several millions to tens of millions of years of fossilised planktonic foraminifera can be preserved without major interruption to the record. Because of this, and as initially discovered by the oil industry in the early 1920s, planktonic foraminifera make useful biostratigraphic markers (Pearson et al., 2006). As biostratigraphic schemes developed over the past 100 years, planktonic foraminifera taxonomic frameworks changed as a necessary step to improve the biostratigraphic resolution. Consequently, planktonic foraminifera are one of the longest ranging and taxonomically well-documented fossil groups in use today. This particular feature of the planktonic foraminiferal record has made it very interesting for studying deep-time climate change (e. g. Pearson et al.,

2008; Wade et al., 2012) but also evolutionary history and dynamics (Aze et al., 2011; Ezard et al., 2011; Pearson and Coxall, 2014).

3.2 Paleocology of Extinct Planktonic Foraminifera

Since most species and families that existed at the time of the EOT are now extinct it is impossible to rely entirely on modern analogues to investigate life habitat and ecological preferences of extinct groups. Therefore, to investigate the ecologies of the extinct planktonic foraminifera groups stable oxygen and carbon isotopes are applied (e. g. Pearson et al., 2001; Wade and Pearson, 2008; Aze et al., 2011). Depending on the life habitat, the planktonic foraminifera species will have a slightly different $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ signal depending on where in the water column they resided. Species living close to the surface generally tend to display a heavy $\delta^{13}\text{C}$ and a light $\delta^{18}\text{O}$ signal, while deeper dwelling species tend to have heavier $\delta^{18}\text{O}$ and lighter $\delta^{13}\text{C}$ signal (Aze et al., 2011). This pattern is caused by a combination of algal productivity and temperature (Aze et al., 2011). Algal productivity in the surface ocean depletes the ambient sea water of light carbon making the planktonic foraminifera shell isotopically heavier. At the same time warmer temperatures in the surface ocean makes $\delta^{18}\text{O}$ lighter. Consequently as depth increases the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ signals in planktonic foraminifera tests will become heavier and lighter respectively. From the difference in stable isotopes several ‘eco-groups’ has been defined (Aze et al., 2011) some of which are summarized in table 1.

Table 1. Summary of the open ocean eco-groups defined by Aze et al., (2011). The colours of the different eco-groups correspond to the groups defined in this thesis (see Results section) as ‘surface-mixed’ (light green), ‘thermocline’ (dark green) and ‘sub-thermocline’ (blue).

Eco-group	Signature
Open ocean mixed layer with symbionts	Very heavy $\delta^{13}\text{C}$ and light $\delta^{18}\text{O}$
Open ocean mixed layer no symbionts	Heavy $\delta^{13}\text{C}$ light $\delta^{18}\text{O}$
Open ocean thermocline	Light $\delta^{13}\text{C}$ and rather heavy $\delta^{18}\text{O}$
Open ocean sub-thermocline	Very light $\delta^{13}\text{C}$ and very heavy $\delta^{18}\text{O}$

Planktonic foraminifera are highly sensitive to changes in their living environment. Therefore by investigating their assemblage and combining it with knowledge of their ecology, changes in the strength of water mass stratification and nutrient upwelling can be inferred (Wade and Pearson, 2008). Combined with stable isotope analysis biological response to changes in

climate can be investigated (Wade et al., 2007; Wade and Pearson, 2008). However, the response of the assemblage can be complex and difficult to interpret. This is because changes in assemblage is controlled by both abiotic (external e. g. climate change, change in ocean structure etc.) and biotic (internal e. g. competition amongst species) drivers as well as species ecology (Ezard et al., 2011). Abiotic drivers has been shown to have a stronger correlation with extinction risk, while biotic drivers correlate better with speciation potential (Ezard et al., 2011).

3.3 Biological Turnover at the Eocene-Oligocene Transition

It has long been known that the late Eocene to early Oligocene was characterized by major evolutionary turnover among pelagic communities, including the extinction of key Eocene foraminifera groups (Cifelli, 1969; Boersma and Premoli Silva, 1986; Thomas and Gooday, 1996). Significantly, the extinction of the planktonic foraminiferal family *Hantkeninidae* has been chosen to denote the boundary between the Eocene and the Oligocene epochs (E-O boundary) as defined in the international stratotype section at Massignano, Italy (Coccioni et al., 1988). First proposed by Nocchi et al. (1988), this was later accepted as the official marker, and ‘golden spike’ for the E-O boundary globally (Premoli Silva and Jenkins, 1993). In addition to this extinction several other important bioevents occur close to the Eocene-Oligocene boundary. The first is the extinction of the genus *Globigerinatheka* (Premoli Silva et al., 2006), which marks the boundary between planktonic foraminifera biozones E15/E16 (Berggren and Pearson, 2005). Closer to the E-O boundary two separate biostratigraphic events occur, the extinction of the angular turborotalids or *Turborotalia cerroazulensis* group (Coccioni et al., 1988; Berggren and Pearson, 2005), a group of three separate species, *T. cerroazulensis*, *T. cocoaensis* and *T. cunialensis*, and a dramatic reduction in size of the species *Pseudohastigerina micra* (Nocchi et al., 1986; Wade et al., 2011).

Assemblages of planktonic foraminifera had experienced a period of very high taxonomic diversity since the middle Eocene, even rivalling the diversity found in modern assemblages (Ezard et al., 2011). This is because of a climate regime that favoured strong ocean stratification (Fraass et al., 2015), allowing assemblages to diversify. But assemblage diversity was on a decreasing trend which culminated with the largest drop in planktonic foraminiferal diversity seen in the Cenozoic as Antarctica glaciated at the EOT (Ezard et al., 2011). However, the cause of the biological turnover seen in planktonic foraminifera (Wade and Pearson, 2008), but also in many other globally distributed fossil groups (Funakawa et al., 2006; Dunkley Jones et al., 2008; Cotton and Pearson, 2011) across the EOT remains uncertain. This is because the

apparent mismatch between the fossil assemblage records and the climate change events recorded in stable isotopes (Pearson et al., 2008); the main turnover event is focused on a 200 kyr plateau close to the E-O boundary between global cooling and ice growth (EOT-1 and Oi-1), indicating that neither of these climate change events were entirely responsible for the turnover observed in the fossil record.

4. Geologic and oceanographic setting

Newfoundland Margin sedimentary drift deposits were targeted by the International Ocean Drilling Program's (IODP) Leg 342 to recover Paleogene sediments from a high sedimentation rate setting to investigate the geochemical, paleoceanographical and sedimentary history of the North Atlantic (Norris et al., 2014). The main drilling area is made up of two ridges extending out from the tip of the Grand Banks, the Southeast Newfoundland Ridge and its subsidiary projection the J-anomaly ridge. These features originated alongside the mid-Atlantic ridge in the mid-Cretaceous (Tucholke and Ludwig, 1982) and the sedimentary coverage is Late Cretaceous to Paleogene in age, making these drift deposits some of the oldest of its type currently known (Norris et al., 2014).

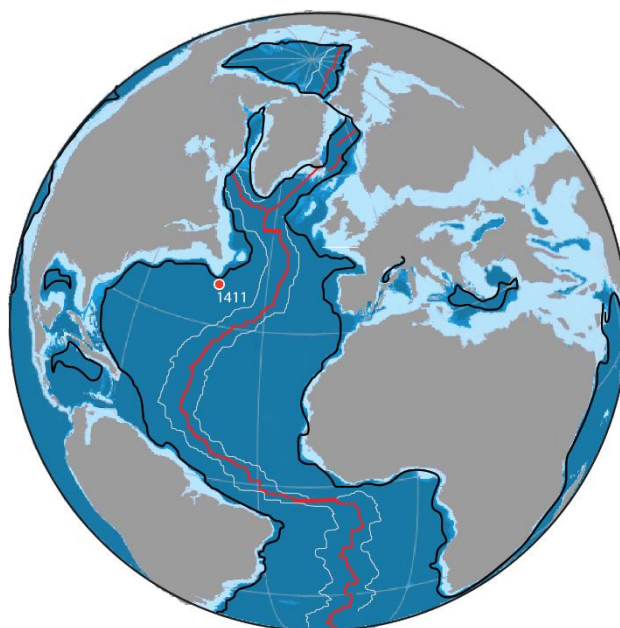


Figure 1. Palaeogeographic and modern oceanic setting of IODP Site U1411 during the Eocene-Oligocene interval (~34 Ma). Plate reconstructions were performed using G-plates, with coastlines adapted from E-O reconstructions of Ron Blakey, Colorado Plateau Geosystems, Arizona USA. Lines: Red = Mid Ocean Ridge 34 Ma; white = position of 56 Ma isochron; Black = continent-ocean boundary.

Site U1411 (Fig. 1) was drilled in the Northeast facing seamounts on the Southeast Newfoundland Ridge (41°37.1'N, 49°00'W) at a water depth of ~3300 m and is considered a mid-depth site, with a paleodepth of ~2850m at 50 Ma (Norris et al., 2014). The 255 m long section ranges from Pleistocene to upper Eocene and consists primarily of clays and nannofossil clays. The sedimentation rate at the Eocene-Oligocene transition has been determined to 5.02cm/k.y (Norris et al. 2014). The EOT section at Site U1411 contain abundant planktonic foraminifera, nannofossils and benthic foraminifera. Planktonic and benthic foraminifera at this

site are described as “glassy” which indicates that preservation is excellent and that the shells unlikely to have been altered by diagenetic processes (Norris et al., 2014).

Today Site U1411 sits close to the northwards flowing Gulf Stream and southwards flowing Labrador Current fronts (Fig. 2A) and experiences both high and low latitude surface current influences (Townsend et al., 2006). This causes a steep latitudinal temperature gradient in the area since the Labrador Current brings cold fresher water from the north and the Gulf Stream brings warm saline water from the tropics which meets off the Grand Banks at Newfoundland Margin. In addition, storms travelling from the North American continent generally converge in this area (Fig. 2B) causing large cyclones that likely influence the depth of the mixed layer and nutrient flux (Townsend et al., 2006). It is unclear where these currents and weather systems were positioned during the EOT since there are few North Atlantic modelling studies focused on the EOT and those that are published mostly focus on North Atlantic deep water formation and deep ocean circulation changes (e. g. Borrelli et al., 2014).

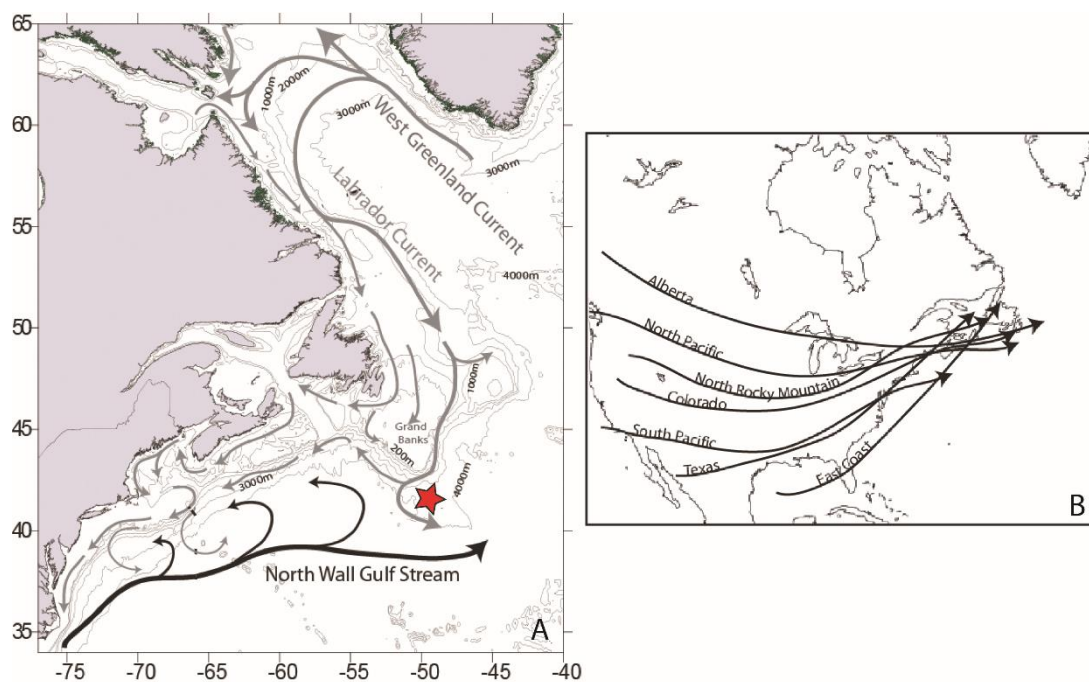


Figure 2. (A) Modern Northwestern Atlantic surface currents and (B) storm tracks across the North American continent converging on the Newfoundland Margin area. Red star indicates the position of Newfoundland Margin. Both A and B are modified from Townsend et al. (2006).

5. Method

5.1 Planktonic foraminifera counts

Species counts were made on 74 samples spanning a 50m long section which includes the EOT at Site U1411. This is a subset of a larger (1600 sample) foraminiferal sample set produced jointly by Stockholm University and the University of Southampton from which high-resolution geochemical proxy records are being generated. This gives a sample resolution in this study of 70 cm and temporal resolution of ~22kyr, spanning most of the EOT section at Site U1411. The sample set presented in this study is a continuous splice from several Site U1411 cores with a common composite depth scale. All depths presented are therefore in meters composite depth (mcd).

For each sample a total of 600 whole planktonic foraminifera specimens were counted. This was carried out in two separate counts of 300 specimens in two separate sieved particle size windows: >180 μm and >63 μm . Counting in the >63 μm fraction is a significant step here since most other planktonic foraminifera assemblages studies focus on species >150 μm . Initial observations of the Site U1411 assemblages indicated significant numbers of small-sized species, i.e. tennitellids, *Dipsidripella*, *Chiloguembelina*, *Globigerina* etc. These groups often dominate the assemblage, as seen in southern high latitude assemblages (Huber, 1991) and their contribution to the assemblage was considered important to document. From the count data relative abundances of planktonic foraminifera species were calculated by dividing the total amount of individuals counted with the number of individuals for any particular species.

The target number of 300 individuals per count was used following the classic work of Shaw (1964), who calculated that to have a 95% chance of counting a species present in 1% of an assemblage at least once, the total of 299 counts are required. The samples were strewn as evenly as possible across a picking tray with a numbered grid (1-45). Grid squares were then randomly selected for counting using a random number generator. This step was necessary to optimize coverage of the picking tray while minimizing bias in the counting process due to gravity sorting of individuals when distributing the sample. The random number generated numbers from 1-45. Individuals were counted in these cells until 300 specimens had been counted. Individual planktonic foraminifera were identified to species level and numbers recorded in count lists. If the same number appeared twice for one size fraction in the same sample the generator was run again until a unique number was selected. If a size fraction contained <300 individual specimen, which was common for the >180 size fraction, all of the

individuals present were counted. When counting in the >63 micron range samples generally had to be split to be able to fit them on the picking tray. This was done using a sample microsplitter to reduce the effect of gravity sorting of small vs. large specimens.

Taxonomic determination of planktonic foraminifera at Site U1411 was based on the taxonomic works of Pearson et al. (2006) and pre-prints of Chapters from the forthcoming Oligocene Atlas of Planktonic foraminifera (Wade et al., in review). Whenever possible the newer taxonomic concepts of Wade et al., (in review), which contains a long over-due and major overhaul of Oligocene taxa, were used. For species restricted to the late-Eocene, or those species not yet added to the new Oligocene atlas, the framework of Pearson et al. (2006) was used.

Biostratigraphic analysis was performed by recording the stratigraphic range of the important late-Eocene to early-Oligocene biostratigraphic marker species that comprise species belonging to the genera *Hantkenina*, *Globigerinatheka*, *Turborotalia* and *Pseudohastigerina*. This provided a low resolution distribution of the important biostratigraphic events that occur across the EOT. The position of the biostratigraphic events were estimated to occur at the midpoint between the sample before and after the last occurrence of the biostratigraphic marker species. This approach allowed for each event to be estimated to within <70 cm of the position as determined in the full (4 cm resolution) Site U1411 sample set.

5.2 Scanning Electron Microscopy

A challenge for Oligocene planktonic foraminiferal taxonomy is that some major taxonomic features, including generic level distinctions are defined by rather subtle differences in shell wall ultrastructure. Thus the U1411 species identifications were assessed using the scanning electron microscope (SEM) imaging of selected well-preserved and representative specimens. For SEM analysis, the selected planktonic foraminifera were mounted in standard orientations (umbilical, edge and spiral views) on steel SEM stubs using a sticky carbon disc and then gold coated using an Agar Sputter Coater producing a coating thickness of 248Å. The samples were then imaged in a Quanta FEG 650 SEM under a high vacuum of 5.37×10^{-6} mbar using a working distance in Z space of 9mm. Attempts were made to obtain 3 views of the same specimen although this was not always possible due to loss or damage of individuals during the remounting process.

5.3 Age model and stratigraphic correlation

An age model was applied to transfer the recorded planktonic foraminifera assemblage data from the depth to the age domain. The age model was provided by Steve Bohaty (National Oceanography Centre, University of Southampton, UK). This was based solely on shipboard magnetostratigraphy (Norris et al., 2014). In addition to the age model, an existing high resolution bulk sediment CaCO₃ stable oxygen and carbon isotope record from Site U1411 (Bohaty et al., in prep.) was used for stratigraphic correlation. This was especially important for identifying the diagnostic stable isotope shifts that characterise the EOT. The interpretation of the stable isotope record will be performed in detail by Bohaty et al., (in prep.) but for the purposes of this study I have interpreted where in the record the stable isotope steps of the EOT occur (see section 6.3).

5.4 Statistical methods

Variability in planktic foraminiferal taxonomic diversity was explored using the Shannon-Weaver index of diversity (Shannon, 1948). The diversity index was calculated from species level data and separate calculations were carried out for the >180 µm and >63 µm assemblages. This index is commonly used to explore biodiversity patterns in fossil communities (Dunkley Jones et al., 2008; Wade and Pearson, 2008) by taking into account the number of individual species and combining it with the dominance of any single species. Therefore, lower H' values indicate less diverse and more dominated assemblages and higher H' indicate more diverse and even assemblages. H' was calculated from equation 1, where p_i is the proportion of individual belonging to the i th species.

$$H' = - \sum_{i=1}^R p_i \ln p_i \quad (1)$$

6. Results

6.1 Preservation of Planktonic foraminifera

The quality of planktonic foraminifera at Site U1411 is generally excellent, with specimen displaying glassy preservation in light microscope, and features indicating well preserved material in SEM, throughout the studied section. For example, smooth test surfaces, spine holes, pustules, complete-rounded pores and, when broken, the remnants of the organic calcifying layer (Fig. 3), could be identified in SEM. Some specimens show evidence of mild dissolution and surface etching and/or infilling of pores and apertures with what appears as calcite, of primarily the larger specimen, but this is only seen in a handful of samples. SEM images indicate that planktonic foraminifera at this site are not largely affected by diagenetic processes such as recrystallization by displaying clean and non-granular test walls.

A common feature of the planktonic foraminifera assemblages at Site U1411 is the presence of a gametogenic calcite layer. Gametogenic calcite is an ontogenic thickening of the planktonic foraminifera wall that occurs as the test matures (Hemleben et al., 1989). This is seen most commonly in species in the $>180\mu\text{m}$ range. In the Site U1411 EOT planktonic foraminifera, gametogenic calcite is a common feature in some genera such as *Catapsydrax* (Olsson et al., 2006) but at Site U1411 it also occur in groups like *Hantkenina*, *Subbotina*, *Dentoglobigerina* and *Turborotalia* (e. g. Appendix 1, Plate 6, 3a), species that are not normally reported to display this feature (P N Pearson et al., 2006).

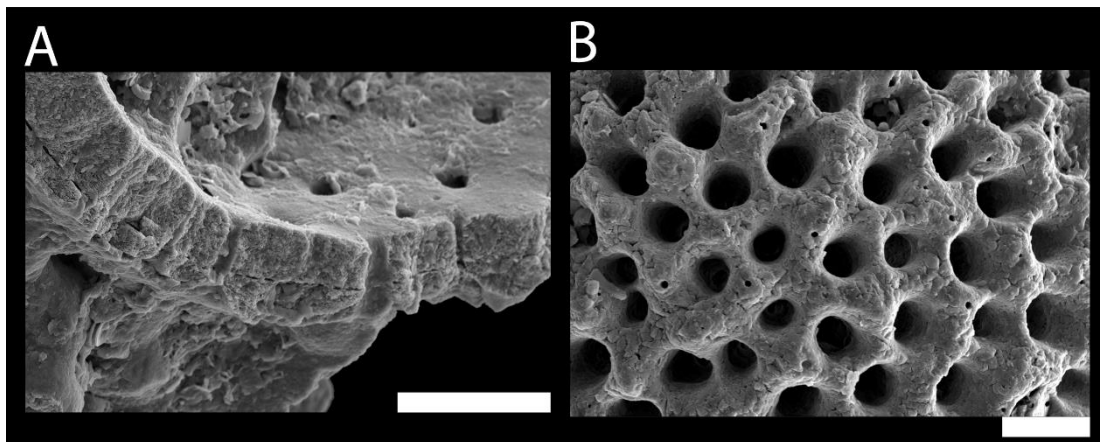


Figure 3. Planktonic foraminifera test ultrastructures visible through SEM imaging. (A) Remnants of the organic calcifying layer from which the foraminifera produces the calcite that forms the test, from species *Subbotina* sp. 1 (IODP Sample U1411-20H-4, 6.5-8 cm, late Eocene zone E15). (B) Image of test wall from *Globoturborotalita gnaucki* (IODP Sample 1411C 12X-5, 2.5-4cm, late Eocene zone E15) displaying smooth test wall, very clean rounded pores and on the pore ridges clear spine holes. Scale bar: A = 20 μm , B = 10 μm .

Reworked planktonic foraminifera are present in most samples in the studied section. They vary in abundance and are sometimes a common or even abundant part of the assemblage. However, the reworked planktonic foraminifera are easily separated from the in-situ ones by the state of their preservation (Fig. 3). The reworked specimen display a “frosty-white” test commonly covered in black dots in light-microscope, along with heavily recrystallized test walls in SEM, which make them easily distinguishable from the in-situ assemblage that has a well preserved “glassy” test wall. Most of the reworked specimen observed are common mid-Eocene taxa, such as *Acarinina* and *Morozovella*, which go extinct before the initiation of the EOT (P N Pearson et al., 2006), while some specimen are from the long ranging genus *Pseudohastigerina*.

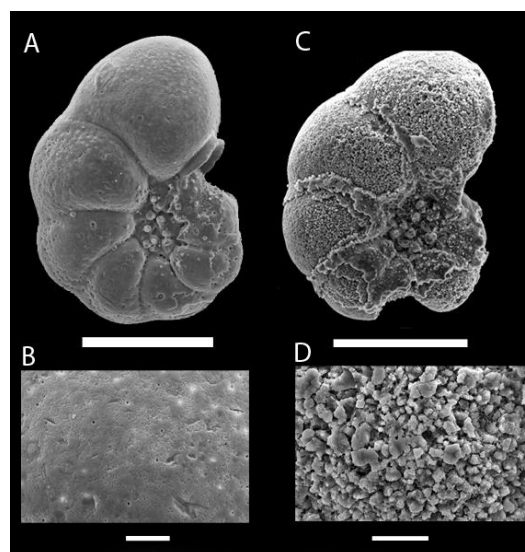


Figure 4. Comparison of the state of preservation between an in-situ (A-B) and reworked (C-D) *Pseudohastigerina micra* in SEM. Scale bars: 100 µm (whole specimens), 10 µm (close-up images).

6.2 Biostratigraphy

Table 2. Identified biostratigraphic events at Site U1411. Top refers to the first sample without the biostratigraphic marker and bottom the last sample with the same marker. Mid is the midpoint between top and bottom, biostratigraphic events are always estimated to occur in the midpoint between the top and bottom samples.

Sample		Age	Zone	Marker Event	Age (Ma)	Depth (mcd)		
Top	Bottom				Mid	Top	Bottom	Mid
1411C 9H-3 94.5-96	1411C 9H-4 14.5-16	late Eocene	O1/E16	HO <i>Hantkenina</i>	33.939	158.565	159.235	158.9
1411C 9H-4 14.5-16	1411C 9H-4 82.5-84	late Eocene	Within E16	Dwarfing <i>P. micra</i>	33.961	159.235	159.915	159.575
1411C 9H-5 6.5-8	1411C 9H-5 74.5-76	late Eocene	Within E16	HO <i>T.cocoaensis</i>	34.005	160.605	161.285	160.945
1411B 18H-6 30.5-32	1411B 18H-6 98.5-100	late Eocene	Within E16	HO <i>T.cerroazulensis</i>	34.294	169.505	170.185	169.845
1411B 19H-4 130.5-132	1411B 19H-4 50.5-52	late Eocene	E15/E16	HO <i>G. index</i>	34.684	181.505	182.205	181.855

A total of 5 separate biostratigraphic events are recognised at Site U1411 and are presented in table 2. The biostratigraphic events are the highest occurrence (HO), as in the highest mcd in the sediment core where the species occur, of *Globigerinatheka index*, *Turborotalia cerroazulensis*, *T. cocoaensis*, *Hantkenina* and *Cribohantkenina* (referred to as HO *Hantkenina*) along with the dwarfing of *Pseudohastigerina micra* or its HO in the >180 µm

assemblage. The HO of *T. cerroazulensis* and *T. cocoaensis* is separated by roughly 8.9 m but at the HO of *T. cerroazulensis* relative abundance of *T. cocoaensis* drop from 5-6% to very low sporadic occurrences (Fig. 9).

Four (out of five) separate species of *Hantkenina* and *Cribrohantkenina* could be identified at Site U1411 which were the species: *C. inflata*, *H. alabamensis*, *H. nanggulanensis* and *H. primitiva*. Sample 1411C 9H-4 14.5-16cm (159,235mcd) contains the last occurrence of the two genera *Hantkenina* and *Cribrohantkenina*, represented by the species *C. inflata* and *H. nanggulanensis*. The last occurrence of *H. alabamensis* and *H. primitiva* occurs earlier in sample 1411C 9H-5 6.5-8cm (160,605mcd), separating the two extinctions by 1.37 mcd.

6.3 Site U1411 bulk CaCO₃ stable isotope record

The bulk CaCO₃ (Fig 6) $\delta^{18}\text{O}$ values are stable between $\sim 0\text{‰}$ and $\sim -1\text{‰}$ in the late Eocene with cyclic variability of $\sim 1\text{‰}$. Cycles are roughly 100-200 kyr long with shorter cyclic variability superimposed on the longer variability. There is a permanent increase in $\delta^{18}\text{O}$ values above the Eocene baseline variability at 33.7 Ma (~ 150 mcd), where values increase permanently by 1 ‰ . Bulk $\delta^{13}\text{C}$ values in the late Eocene are on an overall decreasing trend from $\sim 1.8\text{‰}$ at the start of the section to $\sim 1\text{‰}$ at 34.2 Ma. At 34.1 there is a permanent increase in $\delta^{13}\text{C}$ of $\sim 1\text{‰}$, from values around 1 ‰ to 2 ‰ . This is followed by a trend of increasing values to the end of the section where values increase by $\sim 0.5\text{‰}$. The $\delta^{13}\text{C}$ display similar cycles as the $\delta^{18}\text{O}$ record, longer cycles with shorter variability superimposed.

This pattern of the stable isotope record is different from the Pacific benthic foraminifera stable isotope records (e. g. Coxall et al., 2005; Coxall and Wilson 2011) where both carbon and oxygen display two steps of increasing values across the EOT. Despite this I have interpreted the shift in $\delta^{13}\text{C}$ at 34.1 Ma as the first step, EOT-1, and the shift in $\delta^{18}\text{O}$ at 33.7 Ma as the second step, Oi-1. It is important to note that the Pacific records are mono specific benthic foraminifera records while the Site U1411 are bulk records, which may explain the difference in appearance.

6.4 Planktonic foraminifera diversity and relative abundance

A maximum of 50 species were identified and their relative abundances and stratigraphic distribution were recorded (both size fractions combined) (Fig. 5 and Appendix 1). Among these, 14 species had extremely low occurrences (typically less than 1-2 %) (dashed range lines in Fig. 5). Planktonic foraminifera specimen of uncertain taxonomic affinity were separated and placed as a group of their own. Two species, *Catapsydrax unicavus* and *Globorotaloides suteri* consistently record relative abundances above >10% in the >180 μm size fraction, while in >63 μm *Chiloguembelina ototara* and *Tenuitella gemma* are most abundant recording relative abundances ranging from 10-50%. In addition, *G. suteri* and *C. unicavus* show contribution of around 10% in the >63 size fraction as well. These observations confirm that small species are an important component of planktonic foraminifera assemblages at Site U1411. The most diverse groups in terms of identified species were the genera *Subbotina*, *Dentoglobigerina* and *Globoturborotalita* recording 10, 7 and 7 unique species respectively.

The total number of 50 species includes both rare species, some of which may be misidentifications, which likely weakens the diversity analysis. The dataset was therefore reduced into a more manageable size using (i) taxonomic subdivisions i.e. based on genus level and generic-level sub-lineages (Pearson et al., 2006; Wade et al., in review) and (ii) habitat/ecological preference. For example, the genus *Subbotina* was divided into two lineages based on taxonomic data and placed in the eco-group (see below) ‘thermocline’ dweller. These groupings are illustrated in table 3. Habitat preferences were determined using existing stable isotope paleoecology data (Pearson et al., 2006; Wade and Pearson, 2008; Wade et al., in review) and new data for Site U1411 EOT assemblages (Breen et al., in prep.)

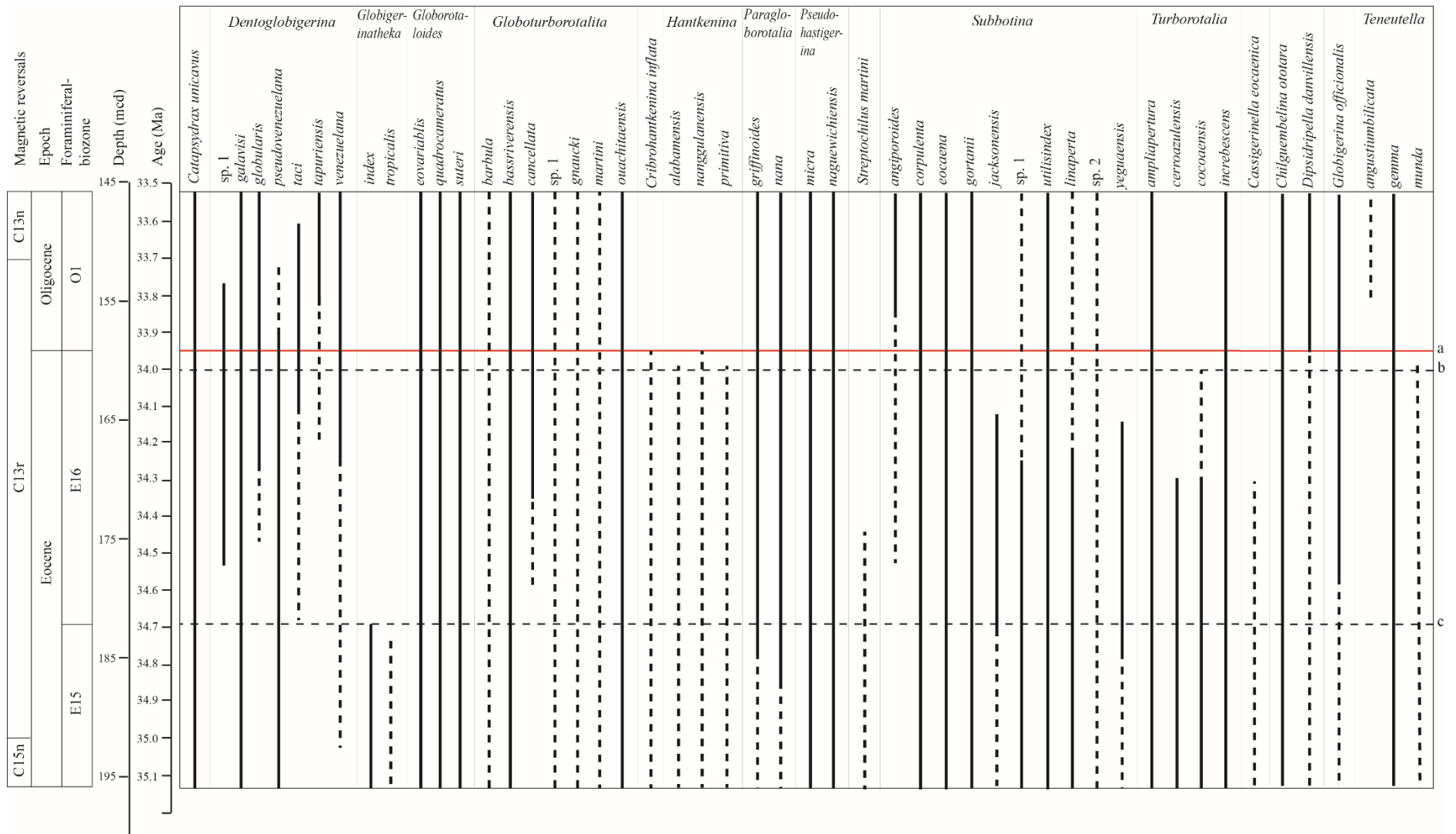


Figure 5. Biostratigraphic range chart of Site U1411 planktonic foraminifera species against planktonic foraminifera biozones (Berggren and Pearson, 2005) and magnetic reversals (Bohaty et al., in prep.). Species are from >180 μ m and >63 μ m size fractions combined. Dashed lines = sporadic/low occurrences. (a) Hantkenina HO, (b) T. cocoaensis HO and (c) Globigerinathea HO.

Table 3. Planktonic foraminifera species reduction. Species are divided into ‘Taxonomic groups’ based on genus level and generic-level sub-divisions. The taxonomic groups are then divided into 3 different eco-groups based on paleoecological habitat preference derived from stable isotope data. If a taxonomic group contain all species of a genus, the genus name is used to name the group, while if several lineages are present the affix ‘group’ is attached.

Eco-group	Taxonomic group	Species
Surface mixed	<i>Globoturborotalita</i>	<i>Globoturborotalita barbula</i>
		<i>Globoturborotalita cancellata</i>
		<i>Globoturborotalita bassriverensis</i>
		<i>Globoturborotalita</i> sp. 1
		<i>Globoturborotalita gnaucki</i>
		<i>Globoturborotalita martini</i>
		<i>Globoturborotalita ouachitaensis</i>
	<i>Globigerina</i>	<i>Globigerina officinalis</i>
	<i>Pseudohastigerina</i>	<i>Pseudohastigerina micra</i>
		<i>Pseudohastigerina naguewichiensis</i>
	<i>Tenuitella</i>	<i>Tenuitella angustiumbilitata</i>
		<i>Tenuitella gemma</i>
		<i>Tenuitella munda</i>
	<i>Chiloguembelina</i>	<i>Chiloguembelina ototara</i>
	T. ampliapertura group	<i>Turborotalia ampliapertura</i>
		<i>Turborotalia increbescens</i>
	T. cerroazulensis group	<i>Turborotalia cerroazulensis</i>
		<i>Turborotalia cocoaensis</i>
Thermocline	D. galavisi group	<i>Globigerinatheka index</i>
		<i>Globigerinatheka tropicalis</i>
		<i>Dentoglobigerina</i> sp. 1
	D. tapuriensis group	<i>Dentoglobigerina galavisi</i>
		<i>Dentoglobigerina globularis</i>
		<i>Dentoglobigerina pseudovenezuelana</i>
		<i>Dentoglobigerina taci</i>
	S. utilisindex group	<i>Dentoglobigerina tapuriensis</i>
		<i>Dentoglobigerina venezuelana</i>
		<i>Subbotina angiporoides</i>
	S. corpulenta group	<i>Subbotina utilisindex</i>
		<i>Subbotina linaperta</i>
		<i>Subbotina corpulenta</i>
		<i>Subbotina eocaena</i>
		<i>Subbotina gortanii</i>
		<i>Subbotina jacksonensis</i>
		<i>Subbotina</i> sp. 1
		<i>Subbotina</i> sp. 2
	<i>Paragloborotalia</i>	<i>Subbotina yequaensis</i>
		<i>Paragloborotalia griffinoides</i>
Sub-thermocline	<i>Catapsydrax</i>	<i>Paragloborotalia nana</i>
	<i>Globorotaloides</i>	<i>Catapsydrax unicavus</i>
		<i>Globorotaloides eovariabilis</i>
		<i>Globorotaloides quadrocameratus</i>
	<i>D. danvillensis</i>	<i>Globorotaloides suteri</i>
		<i>Dipsidripella danvillensis</i>

In this way the initial taxonomic list was reduced to 16 planktonic foraminifera groups (table 3) spread over 3 general depth/ecological habitats, ‘Surface-mixed layer’, ‘Thermocline’ and ‘Sub-thermocline’. These habitat groups are herein referred to as ‘eco-groups’. None of the taxonomic groups defined contains more than one genus, however, certain large genera (*Subbotina*, *Dentoglobigerina* and *Turborotalia*) were split due to them containing several distinct lineages for the identified species in the genera. Hantkeninids were not included in any of the groups on the basis of consistently recording low occurrences in the assemblage (typically under 1% to around 2%). While their overall statistical contribution to the community is considered negligible based on the analysis used here, this family is biostratigraphically extremely important. Thus the relative abundance of hantkeninids and other biostratigraphically important taxa are represented based on actual counts in Figure 9.

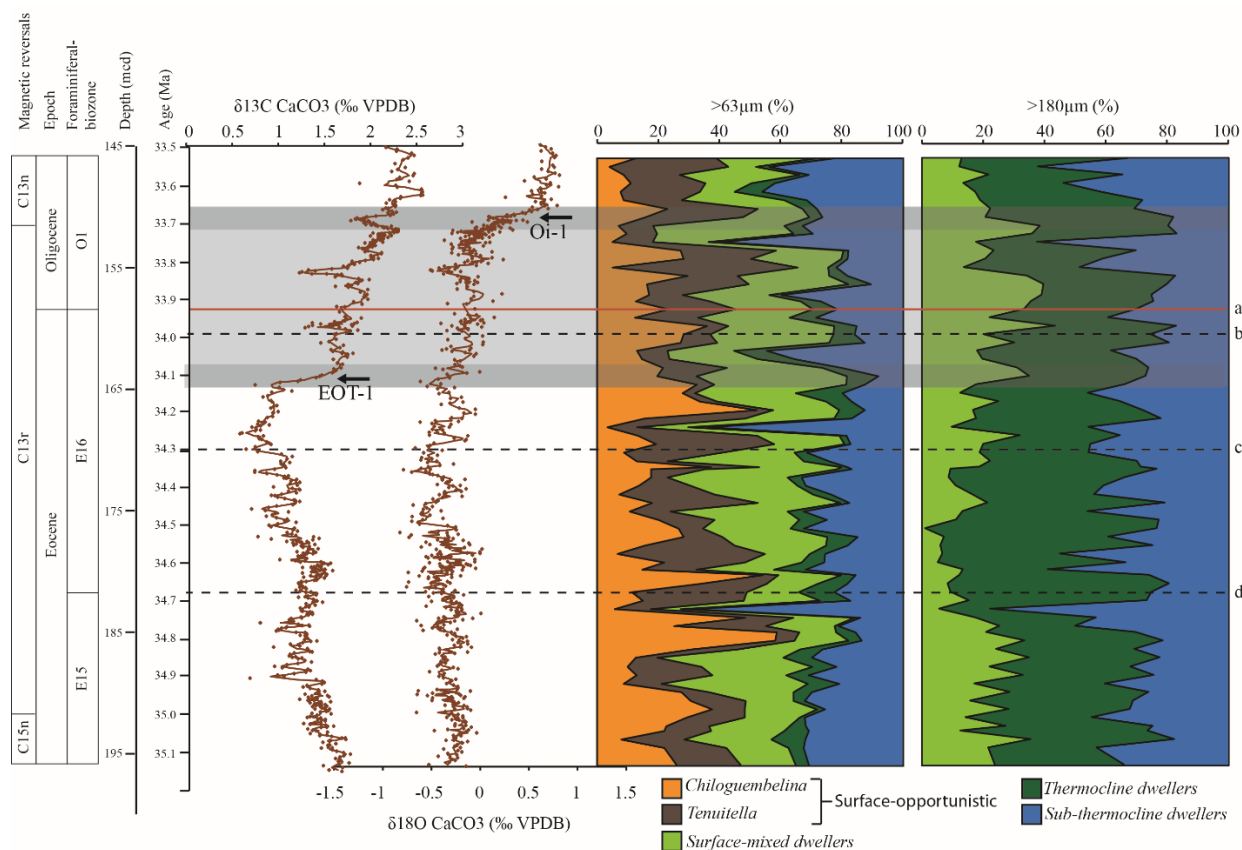


Figure 6. Site U1411 cumulative planktonic foraminifera relative abundance plots of the different eco-groups alongside CaCO_3 stable oxygen and carbon isotopes. In addition to the eco-groups the two most abundant surface opportunistic groups (*Chiloguembelina* and *Tenuitella*) were plotted in the $>63\ \mu\text{m}$ plot to illustrate their total abundance in the assemblage. These species are not present in the $>180\ \mu\text{m}$ size range. Letters to the right are (a) *Hantkenina* HO, (b) *T. cocoaensis* HO and (c) *Globigerinatheka* HO. Gray field indicates range of the EOT, and stable isotope steps (EOT-1 and Oi-1) are marked by dark gray fields and arrows. Solid lines in bulk CaCO_3 data are 3 point running averages.

Relative abundance of the different eco- groups across in the ‘whole sample’ (>63µm) (Fig. 6) show that surface mixed layer taxa dominate making up around 70% of the total assemblage. Of this *Chiloguembelina* and *Tenuitella* are most common. Contributing around 20% each. The sub-thermocline group makes up about 20% of the assemblage and thermocline 6%. When the >180µm assemblage is considered, thermocline dwellers are the most important making up around 50% of the assemblage followed by sub-thermocline and surface dwellers making up 30% and 20% respectively. Between 34.8 Ma to 34.5 Ma there is a zone of low abundance of large surface dwellers followed by gradual recovery reaching peak abundance at roughly 33.8 Ma. Throughout the studied section there is high internal variability in relative abundance amongst the species. Small microperforate surface dwellers display consistently high abundances but also the highest variability in the studied section with some indication of a cyclic pattern on with an amplitude variability of ~20-30%.

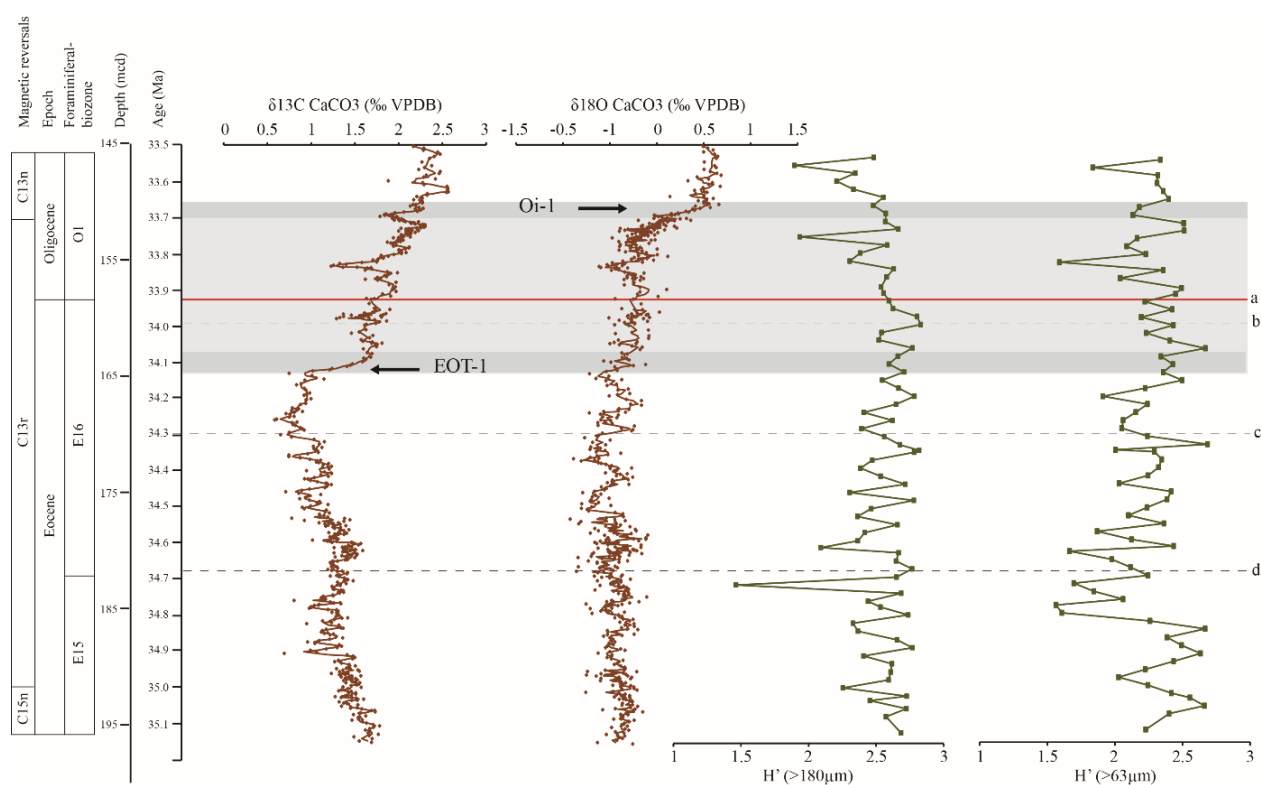


Figure 7. Shannon diversity index H' for >180 µm and >63 µm plotted along bulk CaCO_3 stable isotopes. H' was calculated on both assemblages on species level to follow the method of Wade and Pearson (2008). Letters to the right are (a) Hantkenina HO, (b) *T. cocoaensis* HO and (c) Globigerinatheka HO. Gray field indicates range of the EOT, and stable isotope steps (EOT-1 and Oi-1) are marked by dark gray fields and arrows. Solid lines in bulk CaCO_3 data are 3 point running averages.

Shannon diversity index (H') for the $>180\ \mu\text{m}$ assemblage (Fig. 7) have consistent values between 2.5 and 2.7 from the start of the section until 34.1 Ma were a trend of decreasing values begin and lasts until the end of the section, values now ranging from 1.8 to 2.4 with higher internal variability. One sample at ~183mcd record H' value of ~1.5, much lower than any other sample. This sample is highly dominated by *Catapsydrax* and only a total of 54 planktonic foraminifera were found above $>180\mu\text{m}$. The $>63\mu\text{m}$ assemblage show less of a clear trend but higher variability in H' across the studied section. At roughly 34.8 Ma an excursion towards lower H' occurs, values drop from 2.5 to 1.5 across a few samples. These samples display a high dominance of *Chiloguembelina ototara* which peaks at ~60% abundance in those samples, and the assemblage gradually recovers to values around 2. A rapid increase in H' values begin at 167mcd from 1.9 to 2.4. H' values remain high until the HO of *Hantkenina* were larger fluctuations in values begin.

Within the eco-groups the individual taxa or pre-defined taxonomic sub groups (see above) show interesting patterns of variability in detail. For each eco-group the most common taxa showing clear and significant abundance patterns are examined in detail in Figure 7. Amongst the surface-mixed layer group two groups go extinct during the studied section, *Turborotalia cerroazulensis* group and *Globigerinatheka*. *T. ampliapertura* group increase in abundance from 34.3 Ma remaining steady at 10-20% abundance to the end of the section. *Globoturborotalita* radiates at 34.0 Ma, close to the HO of *T. cocoaensis*. Amongst the thermocline dwellers both *Subbotina* groups display overall decreasing trends, *S. utilisindex* group decreases gradually from the start of the section to the end while *S. corpulenta* show maximum abundance from roughly 34.8-34.5 Ma followed by gradual decrease. *Dentoglobigerina galavisi* group show stable values until the extinction of *T. cocoaensis* followed by a gradual decline in abundance. *D. tapuriensis* group on the other hand radiates from the extinction of *T. cocoaensis* and gradually increases until the end of the section. Interestingly within the thermocline eco-group, overall decreasing abundance of subbotinids broadly corresponds with increasing abundance of dentoglobigerinids. A similar relationship is seen between sub-thermocline dwellers *Globorotaloides* and *Catapsydrax*, with *Globorotaloides* abundance decreasing while *Catapsydrax* increase.

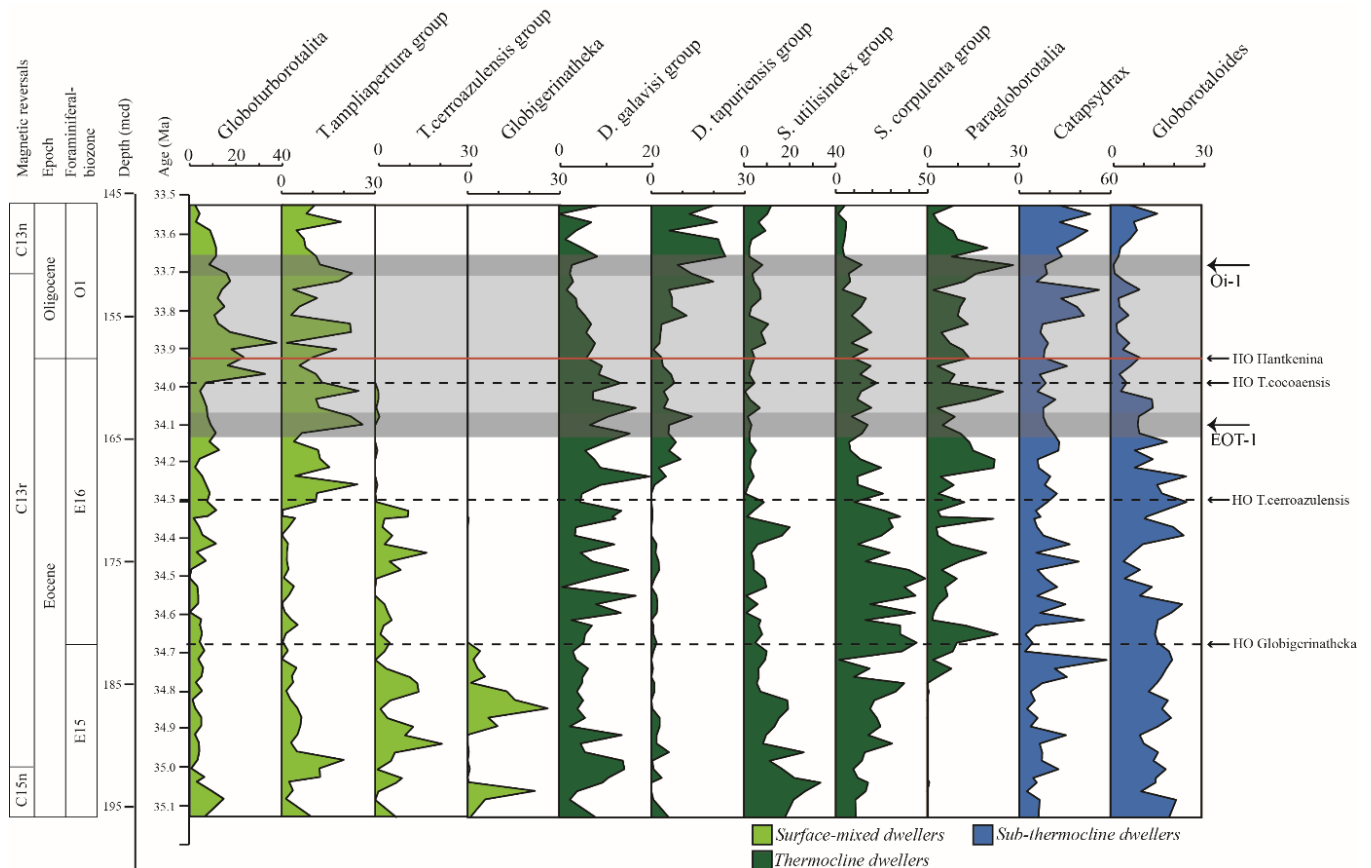


Figure 8. Relative abundances of selected taxonomic groups from the >180 µm assemblage (defined in Table 3). Eco-groups are shown as light green (surface-mixed layer), dark green (thermocline) and blue (sub-thermocline). Gray field indicates range of the EOT, and stable isotope steps (EOT-1 and Oi-1) are marked by dark gray fields and arrows. Smaller arrows indicate important biostratigraphic events.

7. Discussion

7.1 Planktonic foraminifera taxonomy

Planktonic foraminifera are abundant and diverse in the studied section of Site U1411. They are present in all samples and generally yield around 300 individuals in the >180µm size range and >300 individuals in the >63µm size range. This indicates that most of the diversity in the assemblages should be captured following the statistical template of Shaw (1964). The new updated taxonomy from Wade et al. (in review) provides additional taxonomic detail to this important time period by describing the ranges for several new species, especially in the groups *Globoturborotalita* and *Dentoglobigerina*. It is important to note that taxonomic species level identification is to some extent dependent on the taxonomist carrying out the work and different individuals have slightly different taxonomic concepts of a species (Aze et al., 2011). This presents some element of ‘human error’ into taxonomic studies. By presenting SEM images of the species identified in this study (Appendix 1) it is possible for other workers to review my work and possibly refine it in the future.

The high number of identified species at Site U1411 compared to Tropical Indian Ocean assemblages (Wade and Pearson, 2008) may be explained in part by the incorporation of a much larger size range into the assemblage analysis. There are a total of 5 species that are only recorded in the >63µm size range (*Chiloguembelina ototara*, *Tenuitella angustiumbilitata*, *T. gemma*, *T. munda* and *Globigerina officinalis*), which would have been completely overlooked if only the >180µm assemblage had been investigated. The introduction of new taxonomic concepts may also result in an increase in species diversity since more of the morphological variability can be explained by assigning it to a different species rather than grouping a broader range of morphologies under a single species concept. Taxonomic work aside, the planktonic foraminifera community at Site U1411 still consists of a more diverse thermocline and sub-thermocline community than the more shallow and tropical (200-400 m water depth) sites where EOT planktonic foraminifer turnover have been investigated (Wade and Pearson, 2008), this is probably due to the fact that Site U1411 is a true deep ocean site (2850 m paleodepth at 50 Ma, Norris et al., 2014), which allows it to have a fully developed water column stratification including a clear vertical temperature gradient, thermocline and thus more ecological niches to be potentially occupied by planktonic organisms.

It may be possible that interaction between a warm and cold surface current, similar to the modern setting (Townsend et al., 2006) where the Gulf Stream and Labrador Current interact, would support both a high-latitude, as well as a small tropical community consisting of *Globigerinatheka*, *Hantkenina* and *T. cerroazulensis* group. This promotes high taxonomic diversity at a high northern latitude site, which from previous estimations from high-latitude communities should have a species richness of about 15-20 species in the late Eocene (Fenton et al., 2016).

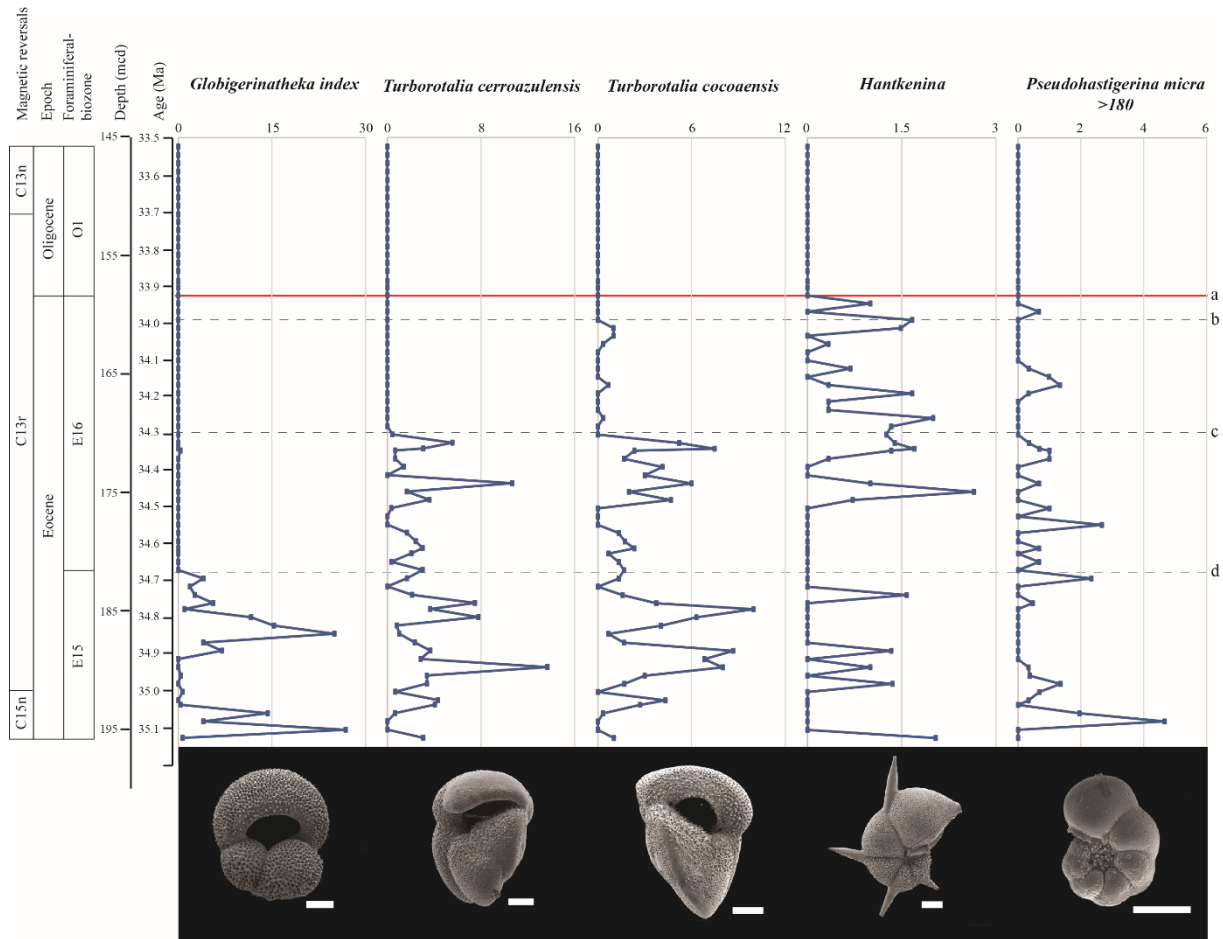


Figure 9. Relative abundances of important planktonic foraminifera biostratigraphic markers at Site U1411. (a) *Hantkenina* HO, (b) *T. cocoaensis* HO and (c) *Globigerinathea* HO.

7.2 Biostratigraphy

The late-Eocene/early-Oligocene planktonic foraminifera biostratigraphy at IODP Site U1411 largely follows the described pattern from the international stratotype section at Massignano, Italy (Coccioni et al., 1988). The described bioevents have been recognised at several sites (Coccioni et al., 1988; Miller et al., 2008; Wade and Pearson, 2008; Wade et al., 2012) further strengthening the global significance and robustness of these events, now extending to the North Atlantic Ocean. The separation between the final extinction of the angular *turborotalids* and *Hantkenina* observed at Site U1411 suggests that the important boundary interval is complete without hiatuses (Wade and Pearson 2008). This is also observed at the type section where the two extinctions are separated by 65kyr (Coccioni et al., 1988), but at Site U1411 two events are separated by ~44kyr, which is still close to the type section but may indicate some reworking of the last *Turborotalia cocoaensis* specimens found or that they extended longer at Site U1411 than elsewhere.

The extinctions observed at Site U1411 appear to be less synchronous in general. The most obvious is the 8.9mcd separation between the last-occurrences of *Turborotalia cerroazulensis* and *T. cocoaensis*, a separation in time of ~285kyr. Previous work have observed a slight separation between the disappearance of these two species and it has been attributed to either non-synchronous extinction or reworking (Wade and Pearson 2008). But at Site U1411 the separation is much larger and it does not extend up to the extinction of *Hantkenina* as observed in Tanzania (Wade and Pearson, 2008). This implies that *T. cerroazulensis* may have disappeared much earlier in the North Atlantic, which may suggest a preference for a more tropical climate. This contradicts the conclusion of Pearson et al. (2006) who state that *T. cocoaensis* probably had a more restricted geographical distribution, but the results presented here would suggest the opposite.

The extinction of hantkeninids is also not synchronous at Site U1411, whereas all five species of the family have been shown to disappear together in the E-O type section and Tanzania (Nocchi et al., 1988; Wade and Pearson, 2008). In the new Site U1411 record, the extinction of *H. primitiva* and *H. alabamensis* is separated from *Cribohantkenina inflata* and *H. nanggulanensis* by 70cm (~22kyr), but *Hantkenina* makes up such a small part of the assemblage (see discussion below) that it is hard to determine if this is a real separation or just an artefact of low abundance and sporadic occurrences.

When present, the representation of *Hantkenina* is very low, usually under 1% for any individual species, and occurrences are sporadic. The four identified species never occur together in the same sample. The final extinction of hantkeninids at Site U1411 occurs on a plateau in the stable isotope records between the EOT-1 and Oi-1 shifts in the top half of magnetochron C13r (Fig. 7). This feature has been recognized by other workers (Coxall and Pearson, 2007; Pearson et al., 2008) and that would suggest that the extinction event recorded at Site U1411 is robust, despite the sporadic and low occurrence of hantkeninids in the studied section. In addition, the last-occurrence of a *Pseudohastigerina micra* in the >180 µm assemblage (Fig. 9) could be interpreted as the dwarfing event introduced by Nocchi et al. (1986) associated with the E-O boundary. This event has been used previously to help estimate the E-O boundary in places where hantkeninids were not present in the assemblages (Miller et al., 2008), which further strengthens the case that the last-occurrence of *Hantkenina* and *Cribohantkenina* can be used as the E-O boundary marker at Site U1411.

Site U1411 also contains a robust biostratigraphic event marking the boundary between planktonic foraminiferal biozone E15/E16 of Berggren and Pearson (2005). The extinction of *Globigerinatheka index* (last remaining species of *Globigerinatheka* at Site U1411) is clear, the species had consistent representation in the >180 μm assemblage before extinction and disappeared rapidly at 181.855 mcd. Other important EOT sections e. g. Tanzania (Wade and Pearson, 2008) and St: Stephens Quarry (Miller et al., 2008) does not contain *Globigerinatheka* close to the EOT and therefore cannot resolve the E15/E16 boundary. The presence of this event at Site U1411 provides additional biostratigraphic resolution for the North Atlantic, which might be useful for refining the age model in the future or to compare this section with other sites.

In addition to the established planktonic foraminifera biostratigraphic events the species *Tenuitella munda* has its highest occurrence in sample 1411C 9H-5 6.5-8 cm at roughly 161 mcd (same sample as HO of *Hantkenina alabamensis* and *H. primitiva*) (Fig. 5). Since this species ranges through the whole Oligocene (Pearson et al., in review), its disappearance at Site U1411 may be a local extinction event or a temporary gap in occurrence. Throughout the studied section *T. munda* occurs sporadically and has gaps in occurrence spanning several samples (largest gap = 16 samples) which may indicate that the species could return later in the Oligocene.

7.3 Eocene-Oligocene turnover events in North Atlantic planktonic foraminifera

The turnover of planktonic foraminifera communities at Site U1411 is focused in two main phases. The first phase occur from 34.9-34.3 Ma and is marked by a decline of large surface taxa (Fig. 6), a significant drop in Shannon diversity H' of the >63 μm assemblage caused by a bloom of *Chiloguembelina ototara* (Fig. 7), high abundance of thermocline species and extinction of *Globigerinatheka*. The phase ends with the extinction of *Turborotalia cerroazulensis*, drop in abundance of *T. cocoaensis* and radiation of *T. ampliapertura* (Fig. 8). Although the extinction of *Globigerinatheka* in the late Eocene has been observed at other sites (Coccioni et al., 1988), the response of the rest of the assemblage has not been reported previously. The first phase of planktonic foraminifera turnover primarily affected the surface ocean, causing extinction and abundance drops amongst the larger surface dwelling planktonic foraminifera. Larger taxa can generally be considered more specialized and are more common under oligotrophic conditions (Schmidt et al., 2004), therefore the initial reduction in abundance and extinction of some larger surface species may suggest a sudden and short lived burst of

nutrients into the surface ocean, causing stresses amongst the specialized species while causing blooms of the opportunistic *C. ototara*.

The extinction of *Turborotalia cerroazulensis*, reduction in abundance of *T. cocoaensis* and radiation of *T. ampliapertura* that occur at the end of the first turnover phase (roughly 170 mcd) shows striking similarity with the final extinction of the *T. cerroazulensis* group in Tanzania (Wade and Pearson, 2008) except that it appears to occur much earlier at Site U1411. It has been suggested that this event was caused by cooling of the surface ocean since the surface species *Pseudohastigerina nagewichiensis* record a significant increase in $\delta^{18}\text{O}$ (Wade and Pearson, 2008). At Site U1411 however bulk $\delta^{18}\text{O}$ record lighter values indicating a period with warmer temperatures. It is possible that at higher northern latitudes the *Turborotalia cerroazulensis* group were already under significant stress from their environment and the slight change in temperature caused the dramatic reduction in abundance and extinction of *T. cerroazulensis* much earlier than in the tropics.

The second phase of turnover at Site U1411 occur close to the E-O boundary. At this site it is marked by the extinction of 4 species of Hantkenina, extinction of *T. cocoaensis* and the dwarfing of *Pseudohastigerina micra* (Fig. 9). In addition this phase is accompanied by a significant shift in >180 Shannon diversity H' from generally stable values of the late Eocene to declining values with increased variability, indicating gradually less diverse and more variable assemblages. There is also radiation of *Globoturborotalita* and *Dentoglobigerina tapuriensis* group and reduction in abundance of the long ranging *D. galavisi* group.

Significantly, none of the waves of biological turnover occur in close relation to the stable isotope steps EOT-1 and Oi-1 recorded in bulk CaCO_3 stable isotopes (Fig. 7) indicating that the mechanism behind the turnover is not recorded by these proxies. This is consistent with findings from Tanzania where the main phase of planktonic foraminifera turnover occur on the stable isotope plateau between the two steps of global cooling and ice growth (Pearson et al., 2008; Wade and Pearson, 2008). At Site U1411 the second phase of planktonic foraminifera turnover occur on this stable isotope plateau suggesting that the changes observed at this time have the same cause as the turnover in planktonic foraminifera (Wade and Pearson, 2008), nannofossils (Dunkley Jones et al., 2008), larger benthic foraminifera (Cotton and Pearson, 2011) from Tanzania and Pacific ocean radiolarians (Funakawa et al., 2006).

Cotton and Pearson (2011) discuss several possibilities for what type of event could be the cause, ranging from bolide impacts, supernova explosions and extreme volcanism, but due to lack of geological evidence for these type of events at the E-O boundary they were all discarded. Instead they propose that the extinction events could have been caused by an increase in nutrients to the oligotrophic surface waters of the late Eocene causing extinctions in specialized species of larger benthic foraminifera and planktonic foraminifera groups such as *Hantkenina*, who are believed to have occupied a highly specialized oligotrophic lower photic zone habitat (Pearson and Coxall, 2014).

The increased abundance of *Globoturborotalita* close to the extinction of the *Turborotalia cerroazulensis* group (Fig. 8) may suggest that stratification weakened causing a bloom through influx of nutrients. In contrast to many planktonic foraminifera groups *Globoturborotalita* has one currently living species, *G. rubescens*, which is useful because we can study its habitat preferences directly. Studies on the modern species of *G. rubescens* and other similar species shows that it is successful both during oligotrophic and high-nutrient periods, and its success in high nutrient periods is attributed to increased export production through weakened stratification which increases particulate feeding and symbiont activity (Storz et al., 2009). Therefore, the marked increase in relative abundance of the *Globoturborotalita* group appears to support the idea of Cotton and Pearson (2011) that increased nutrient flux to the surface water caused extinction of the specialized oligotrophic surface taxa and thus favouring generalists such as *Globoturborotalita*. It is likely that when conditions were stable there were no opportunity for *Globoturborotalita* to bloom, but once conditions changed and nutrient rich deep water was upwelled to the surface the group bloomed rapidly and then returned gradually to normal later in the Oligocene.

Diatom abundances from the late Eocene to early Oligocene time suggests an increase in nutrient upwelling in the Southern Ocean, caused by opening of oceanic gateways around Antarctica and the formation of the proto-Antarctic Circumpolar Current (ACC) (Egan et al., 2013). In the Indo-Pacific tropics nannofossil assemblages record a drop in diversity but also a switch from oligotrophic holococcolith taxa to more eutrophic forms (Dunkley Jones et al., 2008), suggesting that simultaneous increases in upwelling of nutrients occurred in several parts of the global ocean across the EOT. All this evidence suggest that increased nutrient transport to the surface ocean across the EOT had a significant impact on the pelagic communities in the global oceans.

7.4 Planktonic foraminifera assemblage and diversity changes across the EOT

Diversity changes recorded by >180 Shannon diversity index H' across the EOT at Site U1411 are generally less extreme and more gradual than Shannon diversity index changes seen in the tropical assemblages, both from planktonic foraminifera and other fossil groups (Dunkley Jones et al., 2008; Wade and Pearson, 2008). This is probably because Site U1411 have a significantly different structure of the assemblage than can be observed in the tropics. The North Atlantic assemblages are dominated by small opportunistic species and cool water/deep dwelling forms and the taxa that go extinct, while present, is present in low abundances (Fig. 9). It is likely that the North Atlantic assemblages already experienced higher nutrient conditions and colder temperatures before the EOT which favoured this type of taxa instead of the possibly more stable tropics where specialist taxa is more common (Wade and Pearson, 2008; Cotton and Pearson, 2011).

This is supported by the occurrence of gametogenic calcite growth on the Site U1411 planktonic foraminifera. Gametogenic calcite is most often found on modern planktonic foraminifera from colder environments (Hembelen et al., 1989), and the occurrence of this in species from the sub-thermocline to the surface-mixed layer groups (e. g. *Turborotalia*, *Hantkenina*, *Catapsydrax*) at Site U1411 suggest an overall colder environment in the North Atlantic. In addition, high abundances of *Catapsydrax* has previously been associated with high nutrient conditions (Olsson et al., 2006), which would suggest that Site U1411 in general was not an ideal place for specialist taxa.

As a result the extinction events observed at Site U1411 did not have a profound and instantaneous effect on the diversity recorded by the Shannon index, but instead the biological turnover was more gradual and affected the internal structure of the assemblage. This is perhaps most obvious amongst the thermocline taxa where over the course of the studied section both of the *Subbotina* groups and one of the *Dentoglobigerina galavisi* groups become outcompeted by more modern forms (Fig. 8). The *Subbotina utilisindex* group experienced a rapid decline at the start of the studied section while the *Subbotina corpulenta* group gradually increases to a maximum of around 40-50% relative abundance (peak between 183-170mcd) during the first phase of biological turnover (discussed above), and then gradually decline to values around 5-10% at the end of the studied section. The *Dentoglobigerina galavisi* group display stable values of around 10-20% during the Eocene but at the extinction of *Turborotalia cocoaensis* the group declines in abundance to 5-10%. At the same time *Dentoglobigerina tapuriensis*

group experienced a massive and rapid radiation from around 10% to about 20-30% relative abundance. Many of the species in the *D. tapuriensis* group are taxa that originated in the late Eocene early Oligocene suggesting that these taxa was better suited for the colder and changing climate than the long ranging forms of the *Dentoglobigerina galavisi* and *Subbotina* groups. *Paragloborotalia* does not show any significant trend since the huge radiation at 185mcd. It is possible that this group filled a completely different thermocline niche than *Subbotina* and *Dentoglobigerina*, which remained largely unaffected during the studied section.

The sub-thermocline community also changed slightly at roughly the extinction event of *Turborotalia cerroazulensis*. The genus *Globorotaloides* experienced gradual decline, from values around 20% to values around 10%. *Catapsydrax* remains stable around 20% of the assemblage during the late Eocene, but radiates to values ranging from 20-50% after the E-O boundary. In contrast to the sub-thermocline and thermocline communities, the surface community experience rapid changes across the studied section. Radiations occur either at the E-O boundary (turnover phase 2) or at the extinction of *T. cerroazulensis* (end of turnover phase 1). *T. ampliapertura* radiates at the extinction of *T. cerroazulensis* and might suggest that this species took over the free niche space occupied by the angular turborotalids when their numbers dropped.

This evidence suggests that the planktonic foraminifera response to climate change in the western North Atlantic is multi-faceted and likely involves both biotic and abiotic drivers. There is response in the entire community, suggesting that the entire water column down to sub-thermocline depths were affected by the turnover at the EOT. Biotic drivers seem to be more important in the deeper communities which change gradually but with small losses in overall abundance, species are replacing each other. While the rapid shifts in abundance of the surface waters suggest that abiotic external drivers are more important, potentially nutrient upwelling from the deep-ocean (see section 7.3).

7.5 Evidence for cyclic variability in planktonic foraminifera assemblage composition

In addition to the key phases of biotic turnover described above, another feature of the planktonic foraminifera assemblage records from Site U1411 are patterns of background amplitude variability in relative species abundance observed through the studied section. The variability, which appears cyclic in nature in some species, suggests that planktonic foraminifera abundance is connected to the cyclic pacing of changes in the Earth's orbit. Spectral analysis of incoming isotope records from Site U1411 have revealed a significant orbital paleoclimate signal in bulk sediment and late Eocene benthic foraminifera stable isotopes (Coxall et al., 2016 EGU abstract; Bohaty et al., in prep.) similar to the paleoclimate heartbeat recorded in equatorial Pacific Oligocene records (Pälike et al., 2006).

In the U1411 records, the species expressing the strongest cyclic variability are the two most common opportunistic microperforate species *Tenuitella gemma* and *Chiloguembelina ototara*. Plotting them against the bulk CaCO₃ isotopic records suggests similarity in the cycle duration between the isotope records and abundance of these two species (Fig. 10). It is likely, therefore, that because of their opportunistic nature they have a stronger response to changes in climate at orbital frequencies that allows them to capture the cycles expressed in stable isotopes. The cycles that are captured in relative abundance is most likely the long 100 kyr eccentricity cycle, however, in this record it is closer to 200 kyr. There is no known strong orbital cycle with this time period, suggesting that the magneto-stratigraphic age model used still requires some tuning.

An issue with comparing the two datasets is the large difference in sampling resolution. In the stable isotope record there are clear high frequency oscillations superimposed on the longer, in this record, 200 kyr cycles. The assemblage data has a resolution of roughly 70 cm (or 22 kyr) while the bulk isotope data has 8 cm resolution and therefore only the longer cycles can be resolved. Therefore there is a distinct possibility for aliasing the assemblage data compared to the stable isotopes. Aliasing may change the shape of the cycle which may be why some cycles are captured while some are not. To test this hypothesis a high resolution investigation of the small opportunistic species with the same sampling resolution as the stable isotope record is necessary.

The cyclic pattern is strongest during the late Eocene where the abundances of *Tenuitella gemma* largely follow the longer cycles. During the Eocene-Oligocene transition the longer cycles disappear and the record seem to be controlled by significantly shorter cycles. At the same time, variability in *T. gemma* is reduced which further suggest that the longer cycles in the record control abundance of this species. Orbital cycles could potentially control the relative abundance of these species in a few ways. (I) Preservation, these species may be more prone to dissolution changes on orbital time scales. (II) Or variation in Earth's orbit causing changes in nutrient availability in the surface ocean similar to what has been suggested for assemblage variation on orbital timescales in the Pacific (Wade et al., 2007). Changes in preservation seems unlikely since planktonic foraminifera are found glassy throughout the studied section, with only minor differences in preservation between samples and would suggest that the abundance variation is controlled by changes in the surface ocean environment.

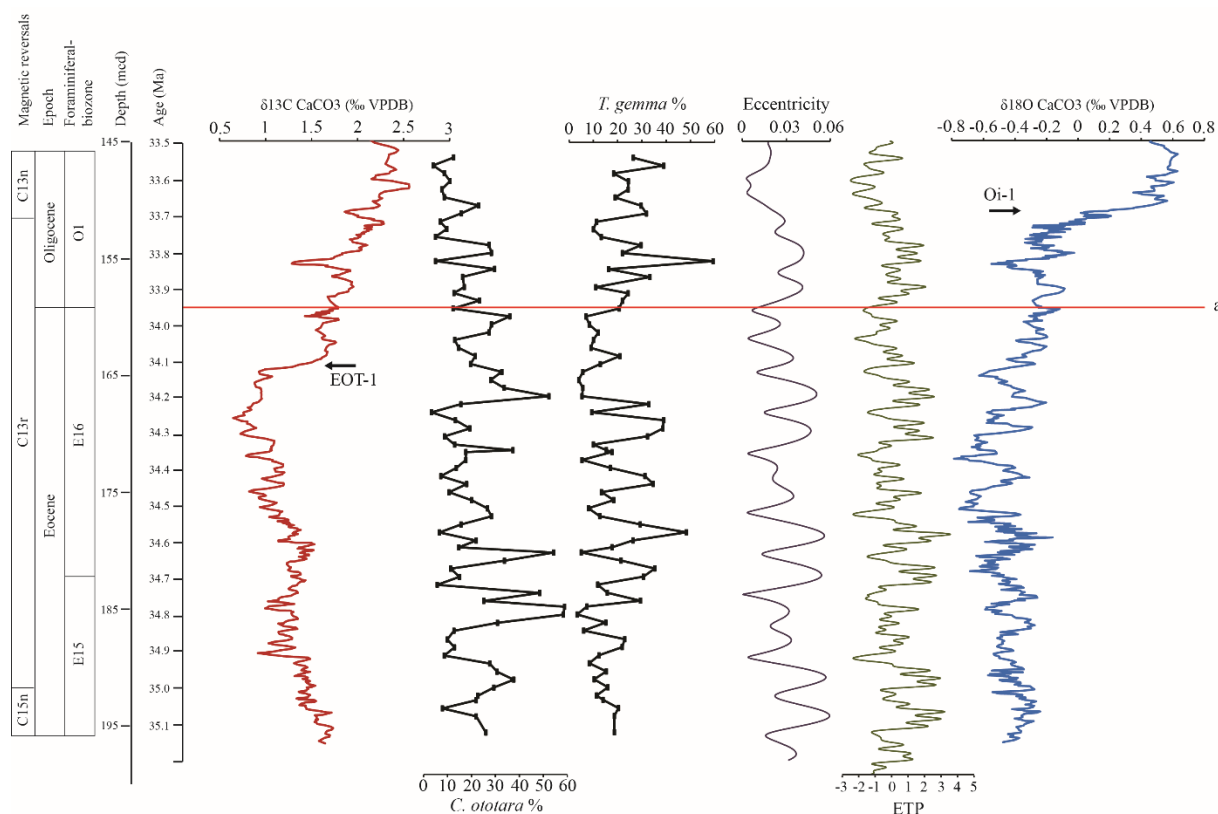


Figure 10. Planktonic foraminifera species *C. ototara* and *T. gemma* plotted alongside CaCO_3 stable isotope records of oxygen and carbon. The data is compared to the idealised eccentricity and ETP (combination of eccentricity, obliquity and precession) from (Laskar et al., 2004). Arrows mark the stable isotope shifts EOT-1 and Oi-1. (a) HO Hantkenina and E-O boundary.

8. Conclusions

The Eocene-Oligocene transition was a period of large global turnover in pelagic communities, but the detailed response in planktonic foraminifera in the North Atlantic has remained largely unknown. This study produced planktonic foraminifera assemblage records from 74 IODP Site U1411 samples covering the Eocene-Oligocene transition and the planktonic foraminifera response to climate change in terms of changes in diversity, community structure and ecology was investigated. The results indicate that turnover in the planktonic foraminifera communities occurred in two distinct phases. The first phase occurs between 34.9-34.3 Ma and primarily caused stresses in the surface community with extinction of *Globigerinatheka* and low abundances of large specialized surface dwellers. The second phase occur close to the Eocene-Oligocene boundary and is marked by the globally recognized extinctions of the *Turborotalia cerroazulensis* group and *Hantkenina*, as well as a shift from stable to variable and declining diversity H' values in the >180 assemblage. The second phase of turnover is likely the globally recognised main turnover phase that has been recognized in the tropics and Southern Ocean and might have been caused by large upwelling of nutrients causing blooms in opportunistic groups like *Globoturborotalita*. In general the turnovers observed at Site U1411 are less extreme and more gradual than has been observed in the past. This is likely because of the high abundance of opportunistic/cool deep dwelling taxa found in the assemblage which was better suited to cope with changing conditions and cooling temperatures. Turnover is observed as gradual changes in deeper dwellers which suggest that competition between groups preconditioned by climate change, rather than the physical changes themselves, was an important mechanism for controlling planktonic foraminifera turnover in the North Atlantic. Finally a pronounced feature of the North Atlantic assemblages is the large variability observed in most planktonic foraminifera groups at site U1411. The species displaying strongest variability are *Tenuitella gemma* and *Chiloguembelina ototara*. Both of these species show some correlation with cycles in the CaCO_3 stable isotope data indicating that changes in the Earth's orbit may be important for controlling planktonic foraminifera abundances on 100 kyr time scales. Orbital cycles may have a potential influence on nutrient availability to the surface ocean, controlling the variation in these species.

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Appedices

Appendix 1: Taxonomic Appendix

List of Identified Species:

Catapsydrax unicavus Bolli, Loeblich and Tappan, 1957

Cassigerinella sp. (probably *C. eocaenica* Cordey, 1968)

Chiloguembelina ototara (Finlay, 1940)

Cribrohantkenina inflata (Howe, 1928)

Dentoglobigerina galavisi (Bermúdez, 1961)

Dentoglobigerina globularis (Bermúdez, 1961)

Dentoglobigerina pseudovenezuelana (Blow and Banner, 1962)

Dentoglobigerina taci Pearson and Wade, 2015

Dentoglobigerina tapuriensis (Blow and Banner, 1962)

Dentoglobigerina venezuelana (Hedberg, 1937)

Dentoglobigerina sp. 1. New species concept presented in the Oligocene Atlas (Wade et al., in review) but since this concept is currently unpublished it cannot be used. This form is characterised by a triangular tooth oriented in front of an umbilical aperture. The species has 3 chambers in the final whorl and the final chamber is compressed.

Dipsidripella danvillensis (Howe and Wallace, 1932)

Globigerina officinalis Subbotina, 1953. Can be quite difficult to identify in light microscope, but generally appears very smooth compared to other macroperforate planktonic foraminifera. Could be confused with *Globoturborotalita bassriverensis* but generally this species have a more compact coiling and is slightly smaller.

Globigerinatheka index (Finlay, 1939)

Globigerinatheka tropicalis (Blow and Banner, 1962)

Globorotaloides eovariabilis Pearson and Huber, 2006

Globorotaloides quadrocameratus Olsson, Pearson and Huber, 2006

Globorotaloides suteri Bolli, 1957

Globoturborotalita barbula Pearson and Wade 2015. Compared to other *Globoturborotalita* this species has a very high spire. This is the only way to identify it in light microscope and SEM imaging is needed to safely identify the species. It is identified by the barbs on its test wall (Appendix 1, Plate 11, 2a-2b) that are only visible in SEM.

Globoturborotalita bassriverensis Olsson and Hemleben, 2006

Globoturborotalita cancellata (Pessagno, 1963)

Globoturborotalita sp. 1. Species concept presented in the unpublished Oligocene Atlas (Wade et al., in review). This form is characterised by a thick arched lip over an open umbilical aperture, 4 chambers in the final whorl and chambers are quite loosely coiled. Is quite cancellate in light microscope.

Globoturborotalita gnaucki (Blow and Banner, 1962)

Globoturborotalita martini (Blow and Banner, 1962)

Globoturborotalita ouachitaensis (Howe and Wallace, 1932)

Hantkenina alabamensis Cushman, 1924

Hantkenina nanggulanensis Hartono, 1969

Hantkenina primitiva Cushman and Jarvis, 1929

Paragloborotalia griffinoides Olsson and Pearson, 2006
Paragloborotalia nana (Bolli, 1957)
Pseudohastigerina micra (Cole, 1927)
Pseudohastigerina naguewichiensis (Myatliuk, 1950)
Streptochilus martini (Pijpers, 1933)
Subbotina angiporoides (Hornibrook, 1965)
Subbotina corpulenta (Subbotina, 1953)
Subbotina eocaena (Guembel, 1868)
Subbotina gortanii (Borsetti, 1959)
Subbotina jacksonensis (Bandy, 1949)
Subbotina utilisindex (Jenkins and Orr, 1973)
Subbotina linaperta (Finlay, 1939)
Subbotina yeguaensis (Weinzierl and Applin, 1929)
Subbotina sp. 1. New species concept presented in the unpublished Oligocene taxonomic atlas (Wade et al., in review). Characterized by an elongated tooth inside a quite open aperture. Some forms have a shorter triangular shaped tooth but similar form in general. The species concept used here is probably a combination of *Subbotina* sp. 1 and *Subbotina* sp. 2 identified by Wade and Pearson 2008 in Tanzania.
Subbotina sp. 2. New species concept presented in the unpublished Oligocene taxonomic atlas (Wade et al., in review). Very similar to *Subbotina* sp. 1 but this form does not have a developed tooth, but rather an elongated lip that reaches over the aperture.
Tenuitella angustiumbilitata (Bolli, 1957)
Tenuitella gemma (Jenkins, 1966)
Tenuitella munda (Jenkins, 1966)
Turborotalia ampliapertura (Bolli, 1957)
Turborotalia cerroazulensis (Cole, 1928)
Turborotalia cocoaensis (Cushman, 1928).
Turborotalia increbescens (Bandy, 1949)

List of planktonic foraminifera taxonomic plates:

Plate 1: *Globigerinatheka* and *Cassigerinella*

Plate 2: *Catapsydrax*, *Pseudohastigerina* and *Globigerina*

Plate 3: *Hantkenina*

Plate 4: *Turborotalia*

Plate 5: *Subbotina*

Plate 6: *Subbotina* continued

Plate 7: *Dentoglobigerina*

Plate 8: *Dentoglobigerina* continued

Plate 9: *Paragloborotalia*

Plate 10: *Globoturborotalita*

Plate 11: *Globoturborotalita* continued

Plate 12: *Globorotaloides*

Plate 13: Microperforate species, *Tenuitella*, *Dipsidripella* and *Chilquembelina*

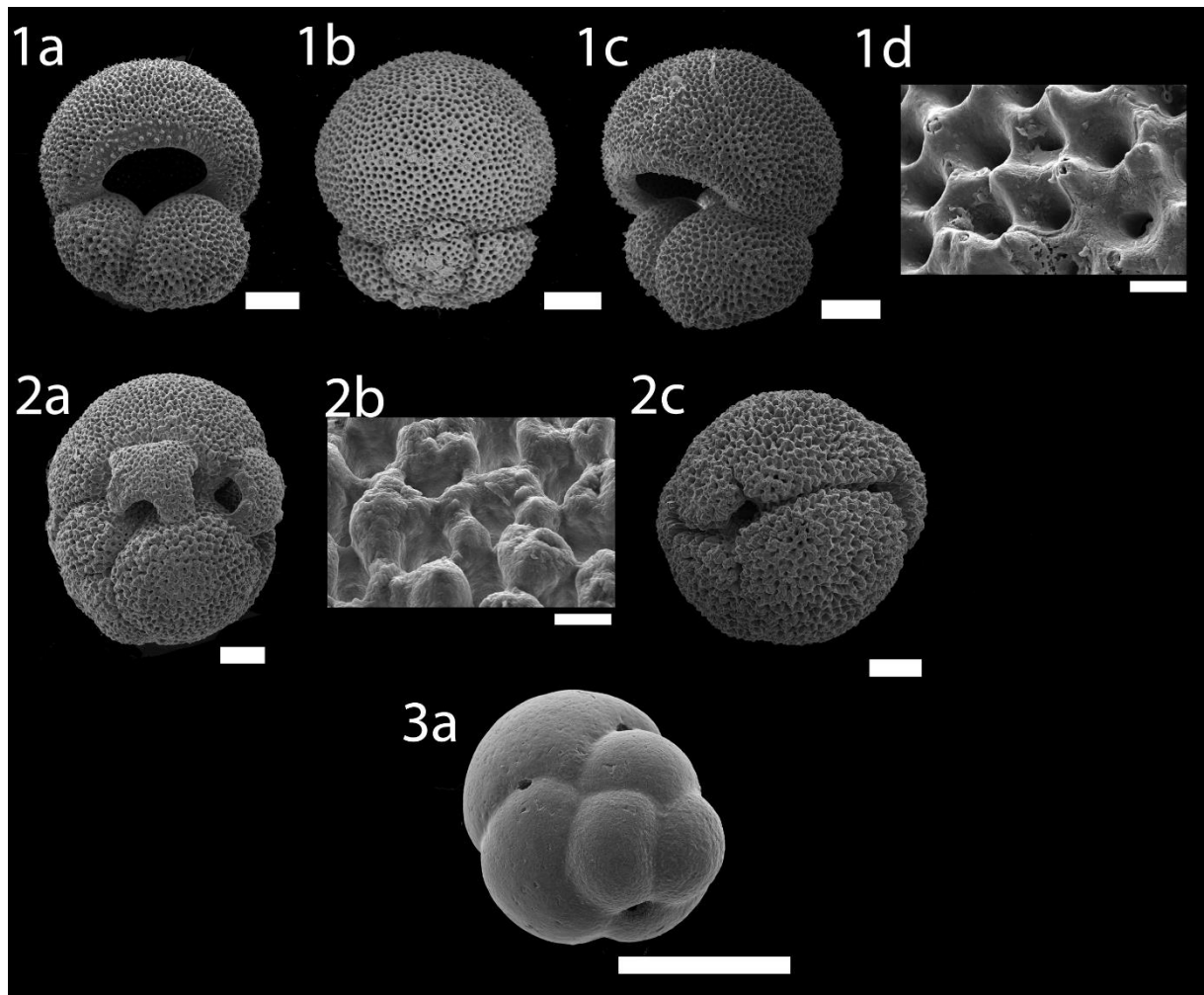


Plate 1. *Globigerinatheka index* **1a-d**, IODP Sample 1411-20H-4, 6.5-8 cm, late Eocene zone E15. *Globigerinatheka tropicalis* **2a-2b**, IODP Sample 1411C 12X-5, 2.5-4cm, late Eocene zone E15. *Globigerinatheka tropicalis* **2c**, IODP Sample 1411C 12X-5, 2.5-4cm, late Eocene zone E15. *Cassigerinella* sp. **3a**, IODP Sample U1411-20H-4, 94.5-96cm, late Eocene zone E15. Scale bars: 100 μ m (whole specimens), 10 μ m (close-up images).

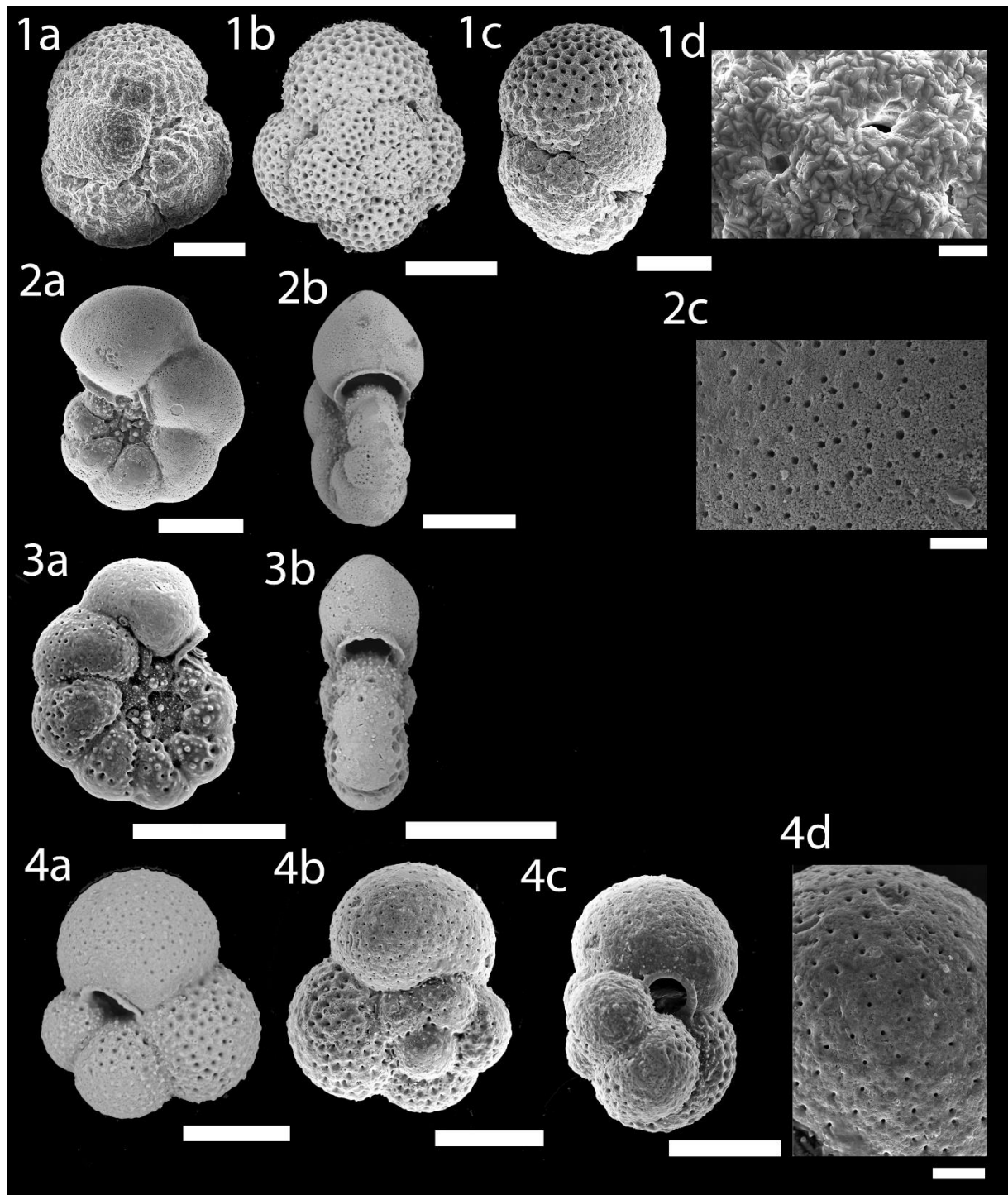


Plate 2. *Catapsydrax unicavus* **1a-1c**, IODP Sample 1411C 11X-5, 90.5-92cm, late Eocene zone E16. *Pseudohastigerina micra*, **2a-2c**, IODP Sample 1411-20H-4, 6.5-8cm, late Eocene zone E15. *Pseudohastigerina nagewichiensis* **3a-3b**, IODP Sample 1411C 9H-3, 70.5-72cm, early Oligocene zone O1. *Globigerina officinalis* **4a-4d**, IODP Sample 1411B 18H-1, 22.5-24cm, late Eocene zone E16. Scale bars: 100µm (whole specimens), 10µm (close-up images), except for **4a-4c** then scale bar 50µm.

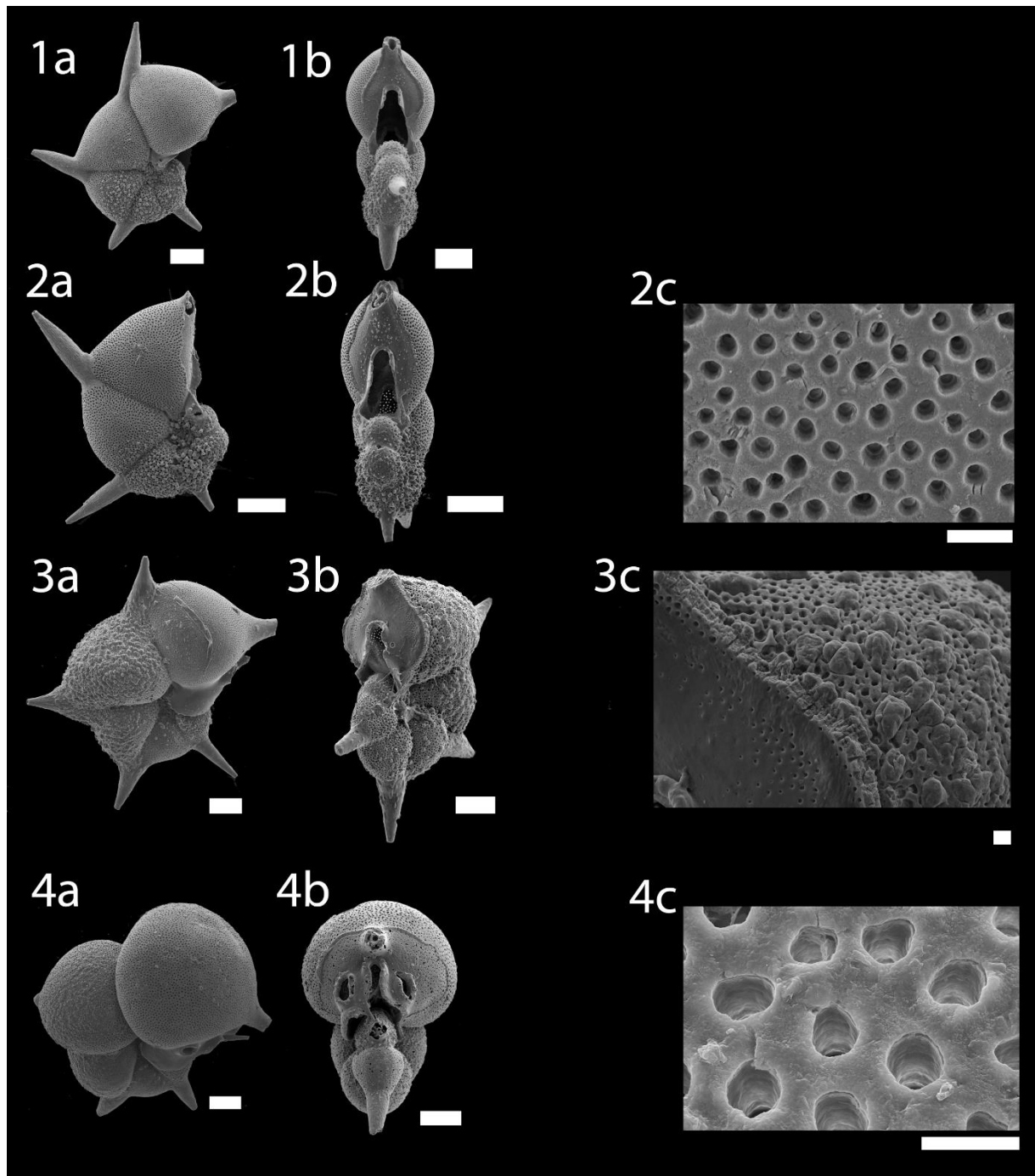


Plate 3. *Hantkenina alabamensis* **1a-1b**, IODP Sample 1411-20H-4, 94.5-96cm, late Eocene zone E15. *Hantkenina primitiva* **2a-2c**, IODP Sample 1411-20H-4, 94.5-96cm, late Eocene zone E15. *Hantkenina nanggulanensis* **3a**, IODP Sample 1411C 11X-3, 114.5-116cm, late Eocene zone E16. *Hantkenina nanggulanensis* **3b-3c**, IODP Sample 1411C 9H-4, 22.5-24cm, late Eocene zone E16. *Cribrohantkenina inflata* **4a + 4c**, IODP Sample 1411C 12X-3, 94.5-96, late Eocene zone E15. *Cribrohantkenina inflata* **4b**, IODP Sample 1411B 19H-5, 130.5-132cm, late Eocene zone E15. Scale bars: 100µm (whole specimens), 10µm (close-up images).

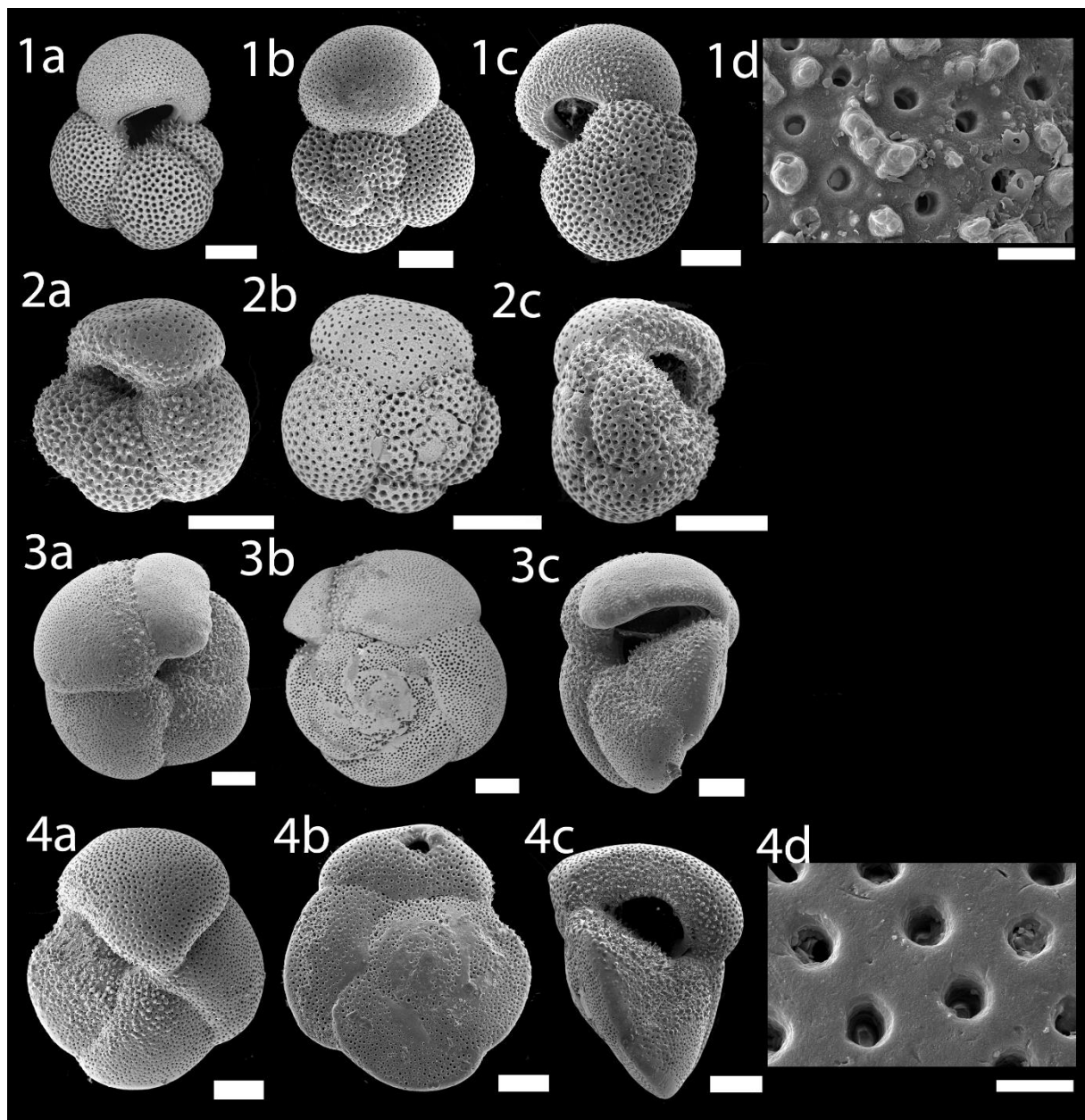


Plate 4. *Turborotalia ampliapertura* **1a-1d**, IODP Sample 1411C 9H-4, 82.5-84cm, late Eocene zone E16. *Turborotalia increbescens* **2a-2c**, IODP Sample 1411-20H-4, 6.5-8cm late Eocene zone E15. *Turborotalia cerroazulensis* **3a-3c**, IODP Sample 1411-20H-4, 94.5-96cm, late Eocene zone E15. *Turborotalia cocoaensis* **4a-4d**, IODP Sample 1411-20H-4, 94.5-96cm, late Eocene zone E15.

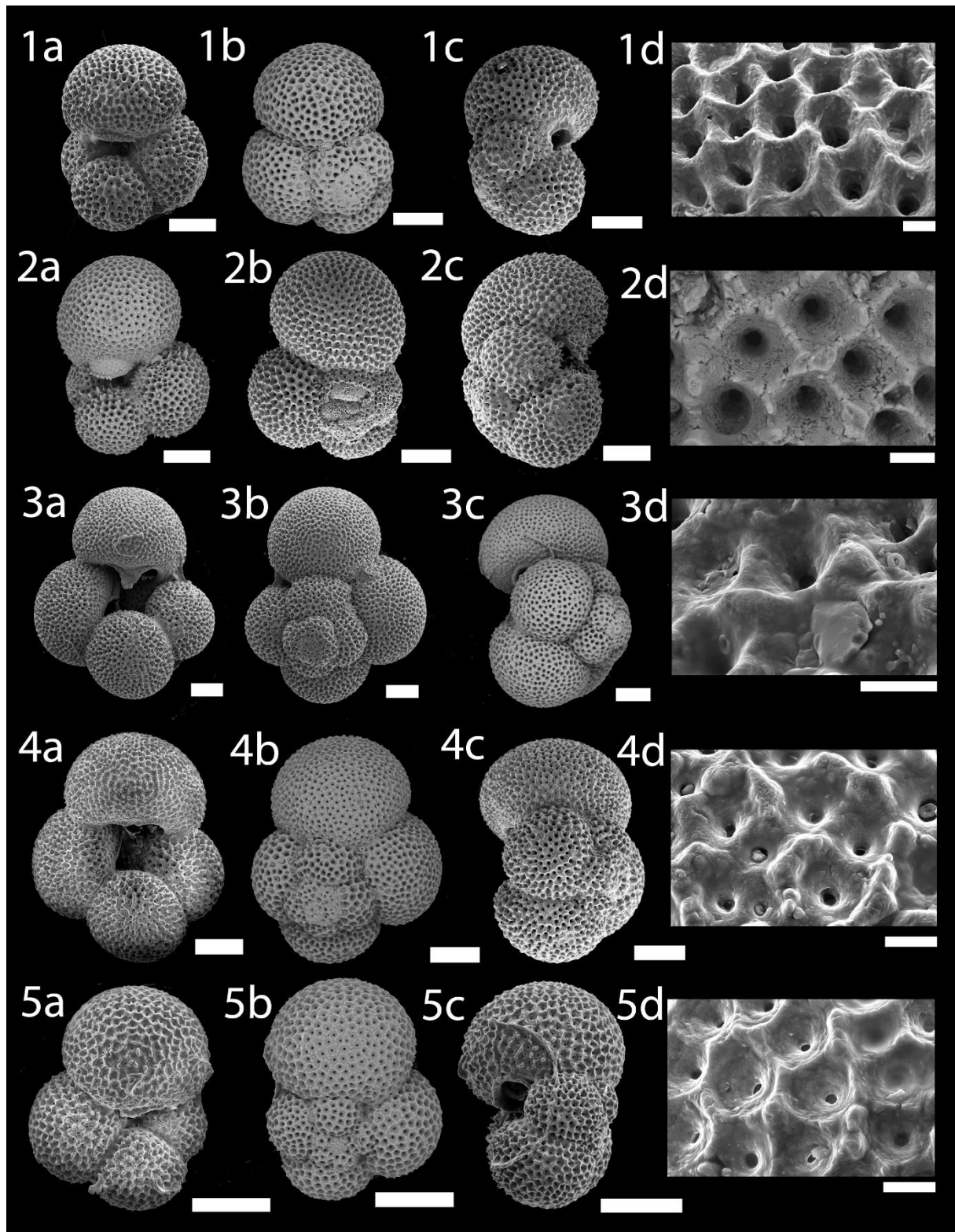


Plate 5. *Subbotina eocaena* **1a-1d**, IODP Sample U1411-20H-4, 6.5-8cm, late Eocene zone E15. *Subbotina* sp. 2 **2a-2b, 2d**, IODP Sample 1411C 6H-5, 38.5-40cm, early Oligocene zone O1. *Subbotina* sp. 2 **2c (edge view)**, IODP Sample 1411B 18H-1, 22.5-24cm, late Eocene zone E16. *Subbotina* sp. 1 **3a-3d**, IODP Sample U1411-20H-4, 94.5-96cm, late Eocene zone E15. *Subbotina corpulenta*, **4a-4d**, IODP Sample 1411C-11X-6, 10.5-12cm, late Eocene zone E16. *Subbotina yeguaensis*, **5a-5d**, IODP Sample 1411C-11X-6, 10.5-12cm, late Eocene zone E16. Scale bars: 100 μ m (whole specimens), 10 μ m (close-up images).

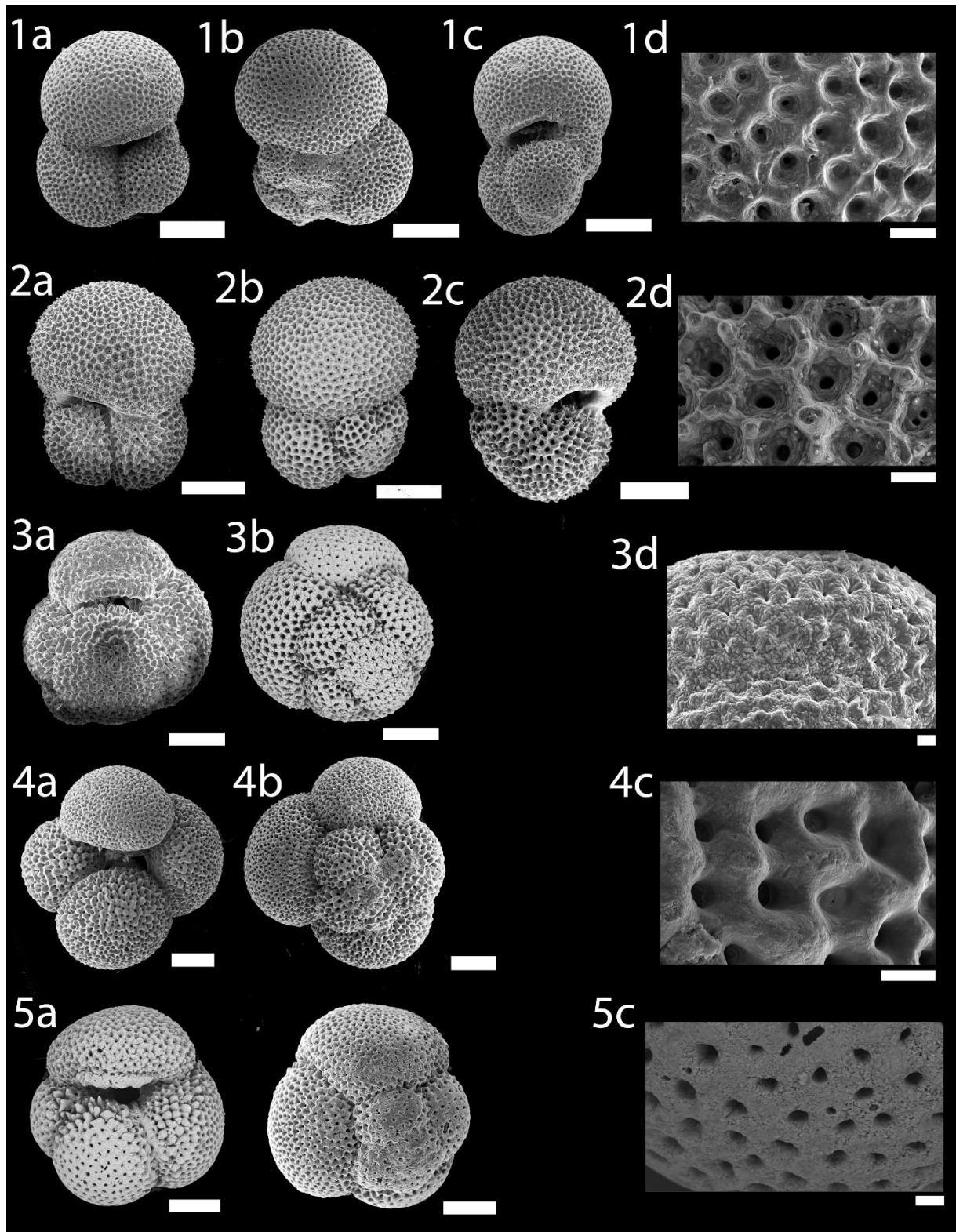


Plate 6. *Subbotina utilisindex*, **1a-1d**, IODP Sample 1411-20H-4, 6.5-8cm, late Eocene zone E15. *Subbotina linaperta*, **2a-2d**, IODP Sample 1411C-12X-3, 26.5-28cm, late Eocene zone E15. *Subbotina angiporoides*, **3a-3d**, 1411C 11X-5, 90.5-92cm, late Eocene zone E16. *Subbotina gortanii* (could potentially be *S. corpulenta*) **4a-4c**, 1411-20H-4, 6.5-8cm, late Eocene zone E15. *Subbotina jacksonensis*/*S. angiporoides*? **5a-5c**, IODP Sample 1411B 18H-1, 22.5-24, late Eocene zone E15. Scale bars: 100µm (whole specimens), 10µm (close-up images).

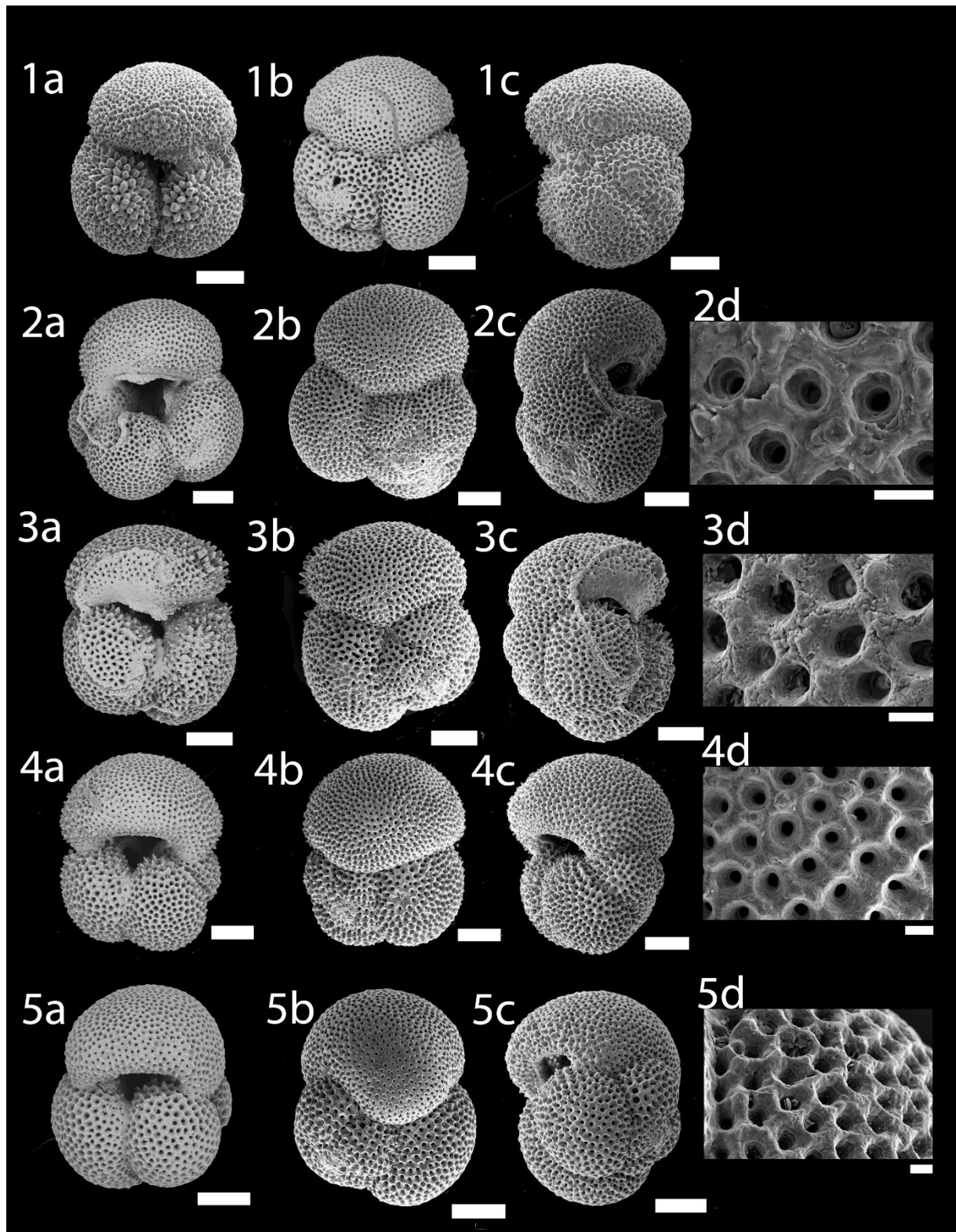


Plate 7. *Dentoglobigerina galavisi* **1a-1c**, IODP Sample U1411-20H-4, 94.5-96cm, late Eocene zone E15. *Dentoglobigerina globularis* **2a-2d**, IODP Sample 1411C 9H-4, 82.5-84cm, late Eocene zone E16. *Dentoglobigerina* sp. 1 **3a-3d**, IODP Sample 1411C 9H-4, 82.5-84cm, late Eocene zone E16. *Dentoglobigerina taci* **4a-4d**, IODP Sample 1411C 6H-5, 38.5-40cm, early Oligocene zone O1. *Dentoglobigerina tapuriensis* **5a-5d**, IODP Sample 1411C 6H-5, 38.5-40cm, early Oligocene zone O1. Scale bars: 100µm (whole specimens), 10µm (close-up images).

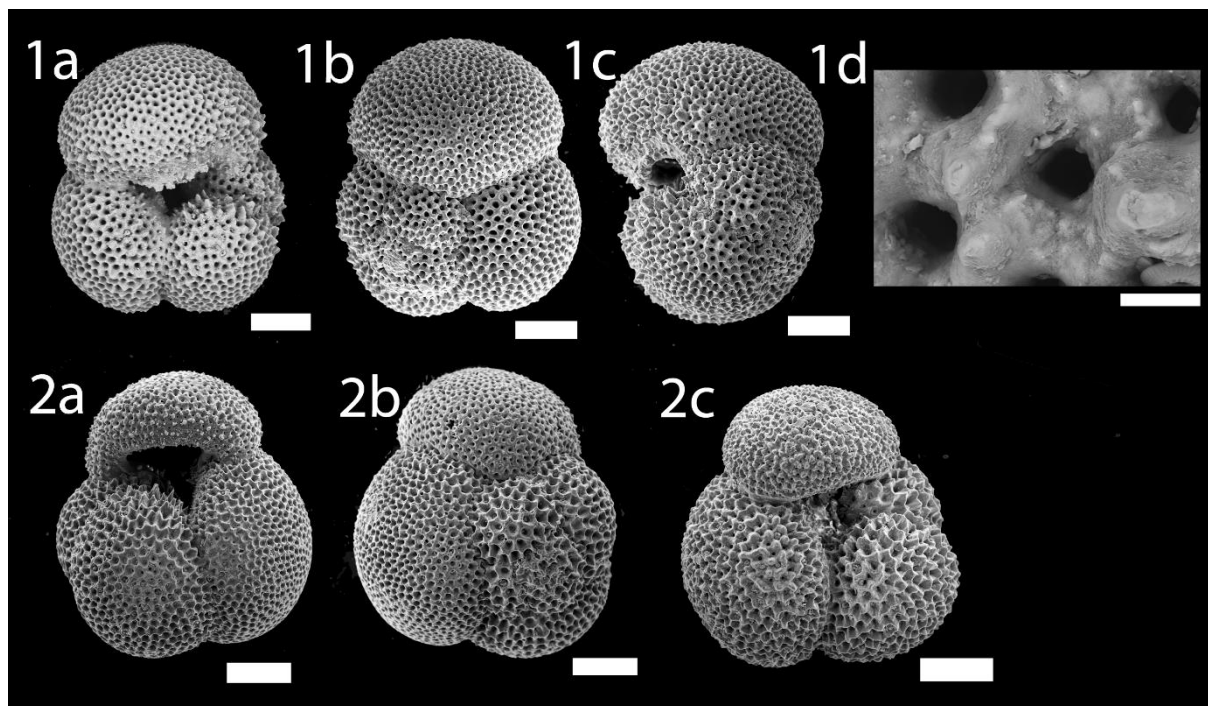


Plate 8. *Dentoglobigerina pseudovenezuelana* **1a-1d**, IODP Sample 1411C 9H-4, 82.5-84cm, late Eocene zone E16. *Dentoglobigerina venezuelana* **2a-2b**, IODP Sample 1411C 8H-4 106.5-108cm, early Oligocene zone O1. *Dentoglobigerina venezuelana* **2c**, IODP Sample 1411C 8H-4 106.5-108cm, early Oligocene zone O1.

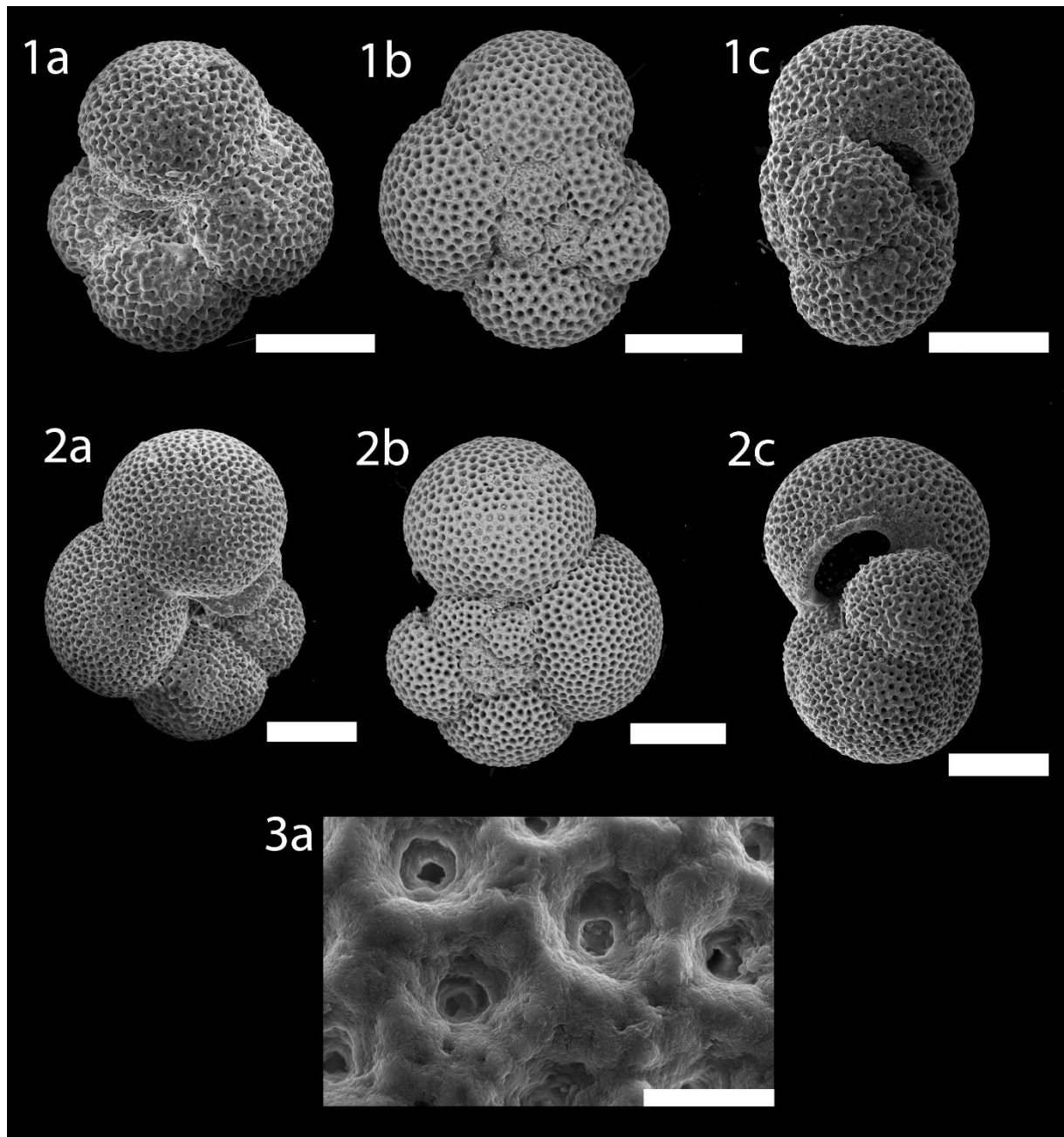


Plate 9. *Paragloborotalia nana* **1a-1c**, IODP Sample 1411B-19H-3, 62.5-64cm, late Eocene zone E16. *Paragloborotalia griffinoides* **2a-3a**, IODP Sample 1411B-19H-3, 62.5-64cm, late Eocene zone E16. Scale bars: 100µm (whole specimens), 10µm (close-up images).

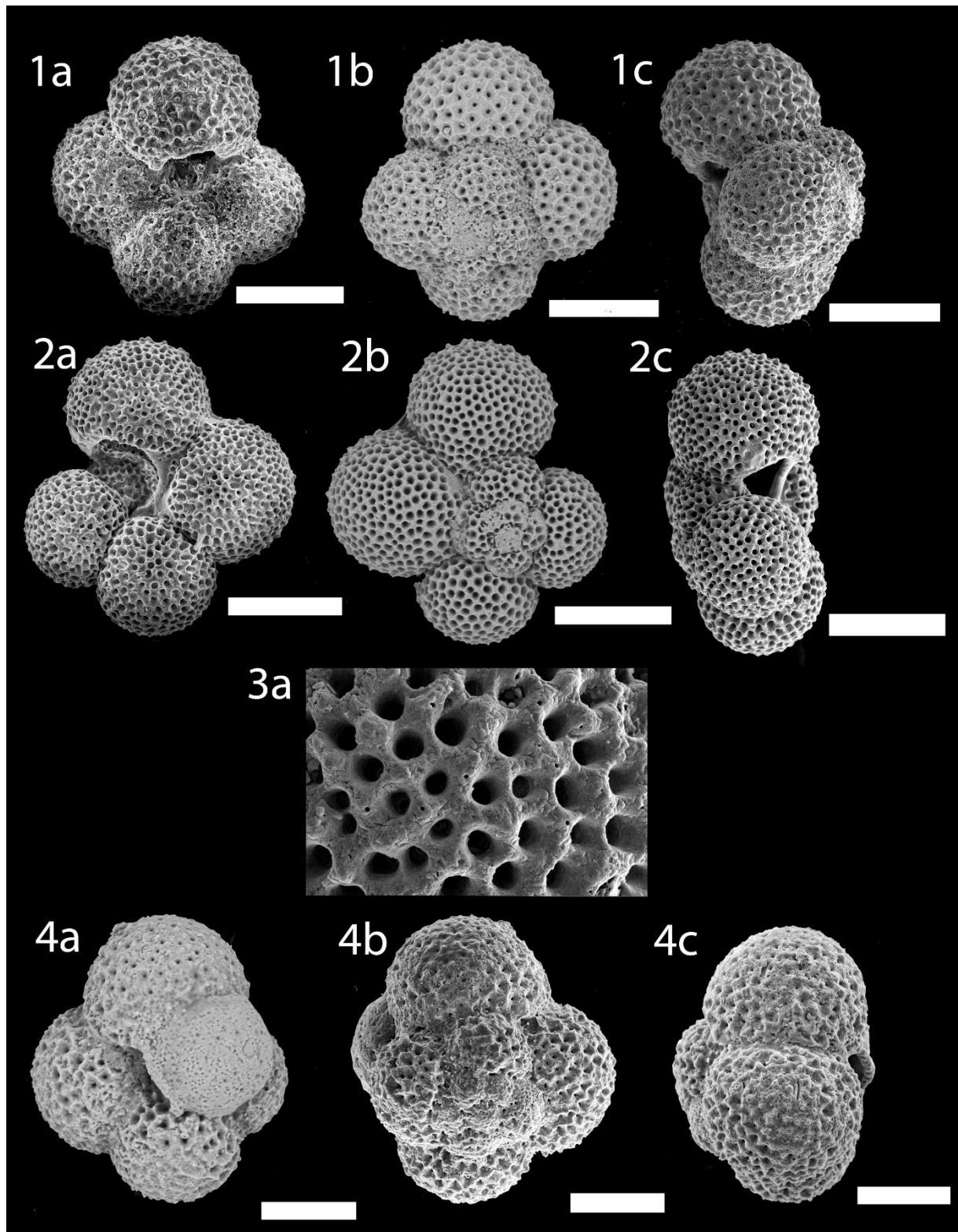


Plate 10. *Globoturborotalita ouachitaensis* **1a-c**, IODP Sample 1411B 19H-2, 142.5-144cm, late Eocene zone E16. *Globoturborotalita gnaucki* **2a-3a**, IODP Sample 1411C 12X-5, 2.5-4cm, late Eocene zone E15. *Globoturborotalita martini* **4a-4c**, IODP Sample 1411C 8H-4, 106.5-108cm, early Oligocene zone O1. Scale bars: 100µm (whole specimens), 10µm (close-up images), except **4a-4c** where scale bar = 50µm.

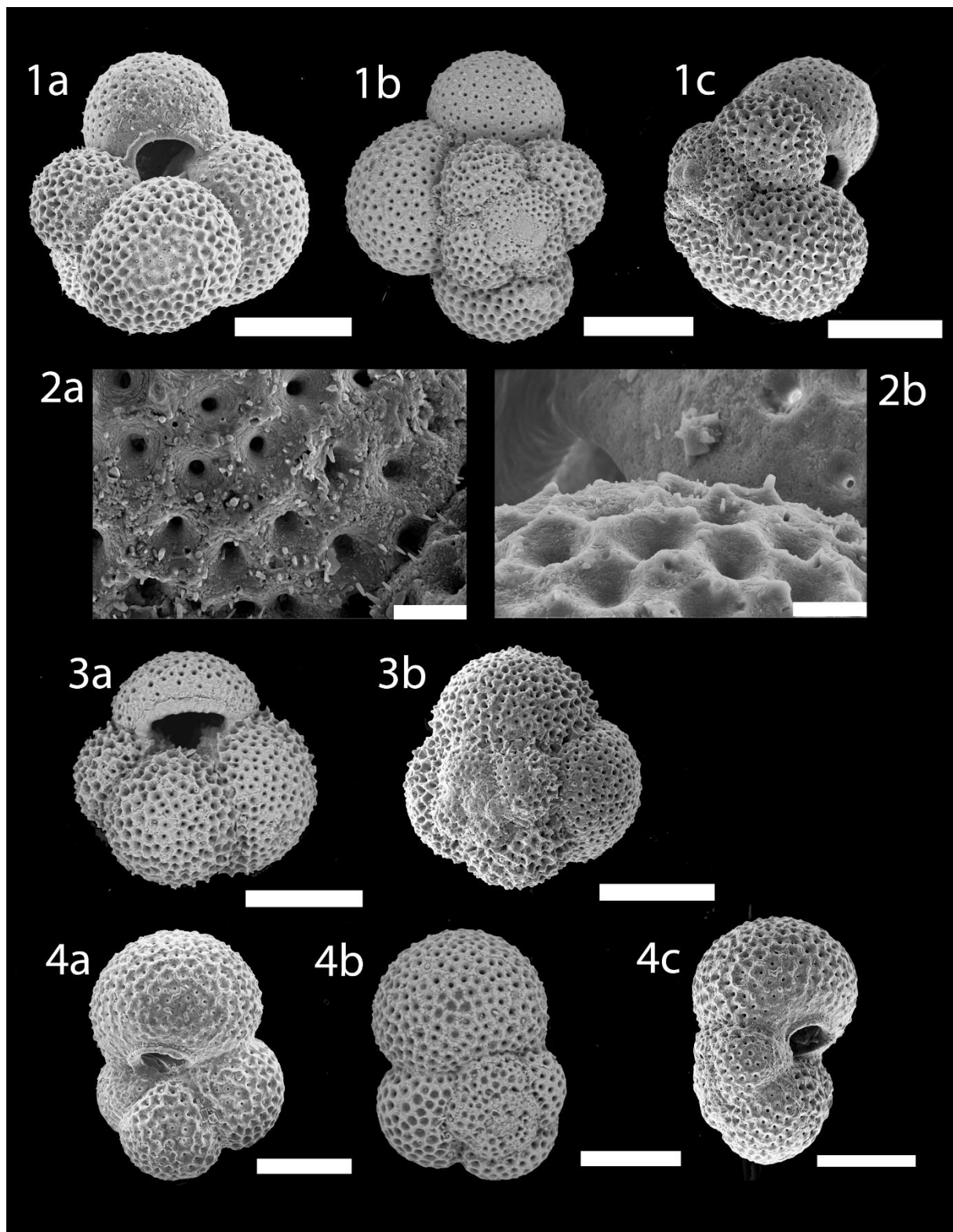


Plate 11. *Globoturborotalita barbula* **1a-2b**, IODP Sample 1411C 11X-2, 126.5-128cm, late Eocene zone E16. *Globoturborotalita* sp. 1 **3a-3b**, IODP Sample 1411B 18H-1, 22.5-24cm, late Eocene zone E16. *Globoturborotalita cancellata* **4a-4c**, IODP Sample 1411B 18H-7, 66.5-68cm, late Eocene zone E16. Scale bars: 100µm (whole specimens), 10µm (close-up images).

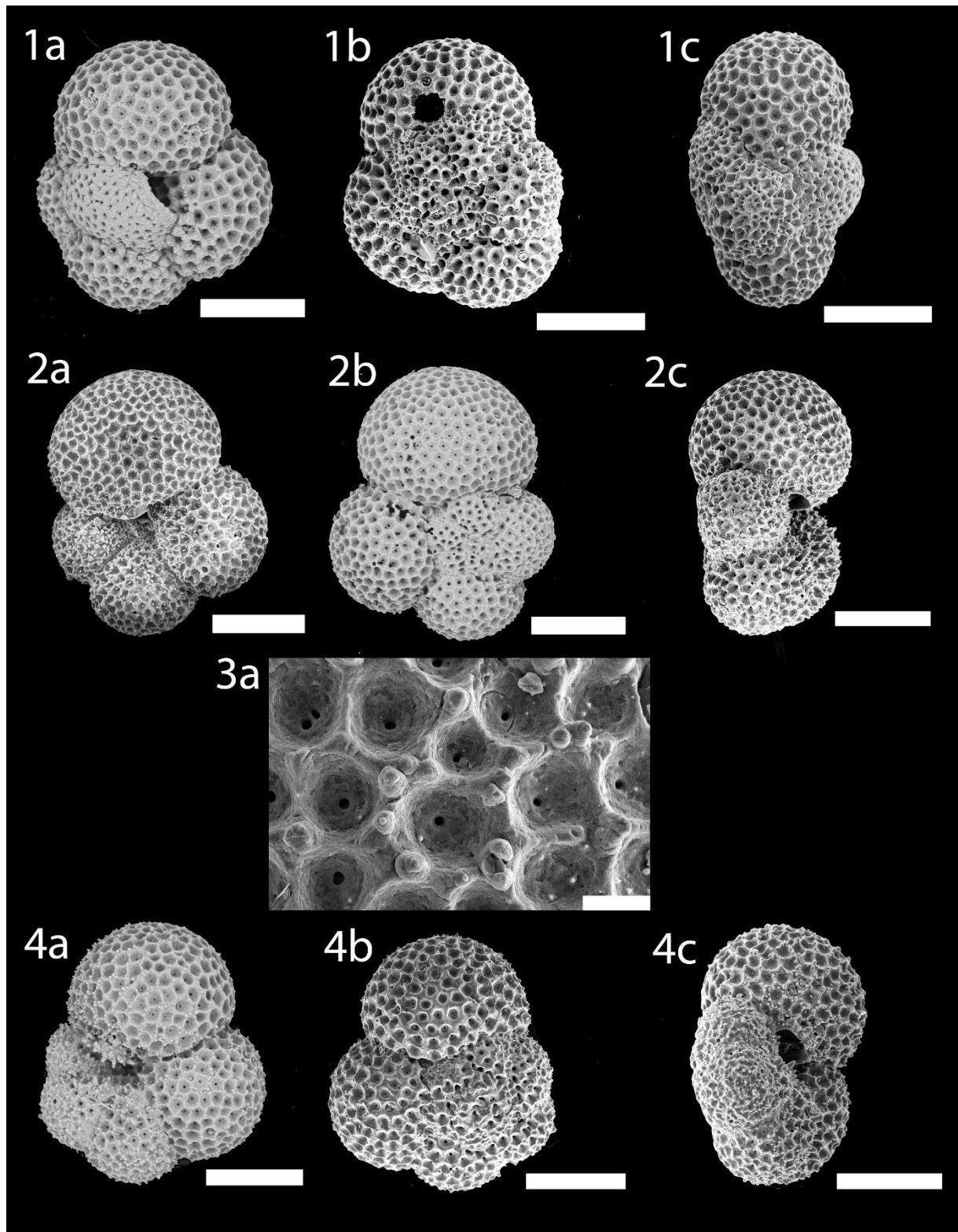


Plate 12. *Globorotaloides suteri* (with bulla) **1a-1c**, IODP Sample 1411B 18H-1, 22.5-24cm, late Eocene zone E16. *Globorotaloides quadrocameratus* **2a-3a**, IODP Sample 1411C 11X-4 114.5-116cm, late Eocene zone E16. *Globorotaloides eovariabilis* **4a-4c**, IODP Sample 1411B 17H-4, 138-140cm, early Oligocene zone O1. Scale bars: 100µm (whole specimens), 10µm (close-up images).

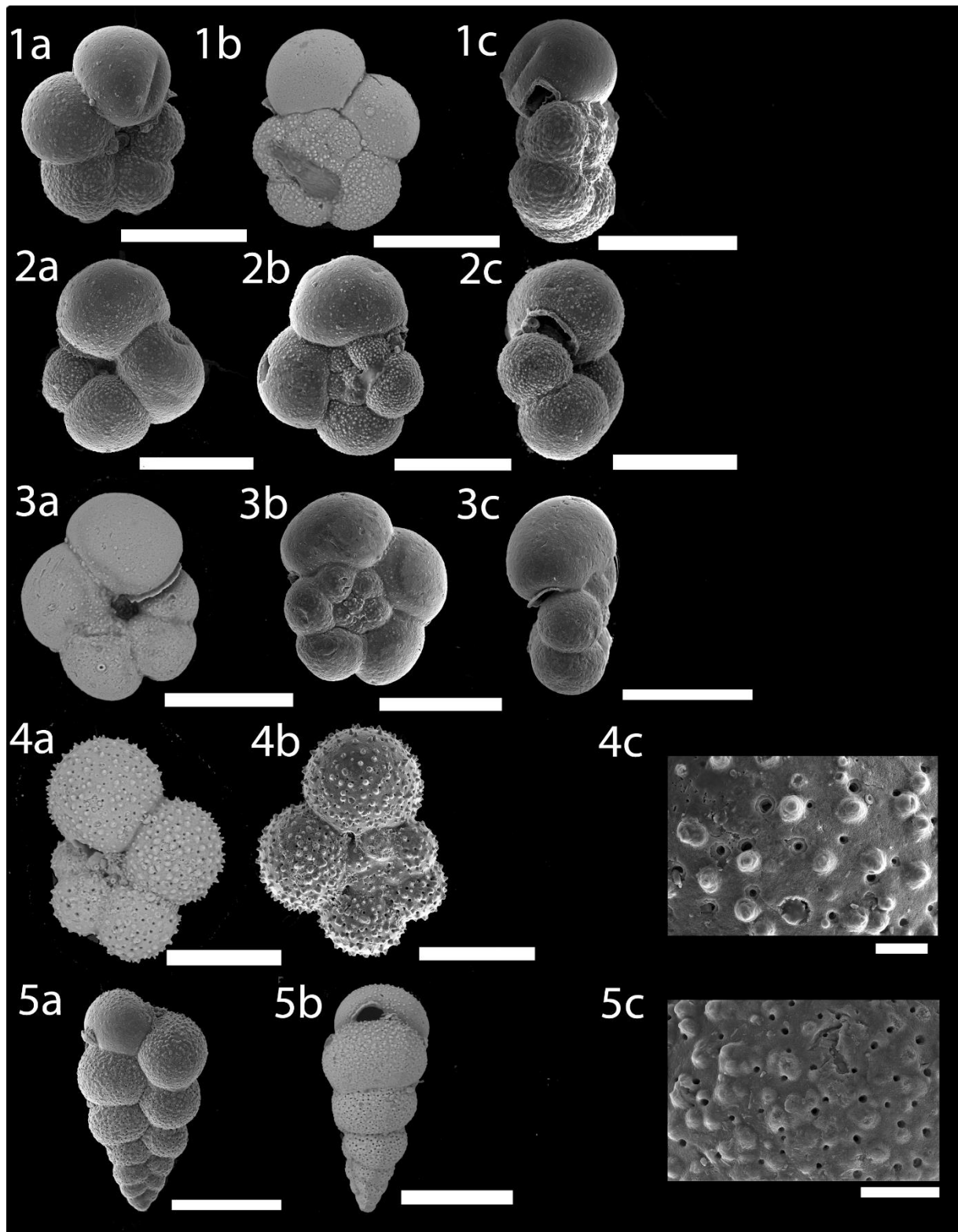


Plate 13. *Tenuitella gemma* **1a-1c**, IODP Sample U1411-20H-4, 6.5-8cm, late Eocene zone E15. *Tenuitella munda* **2a-2c**, IODP Sample U1411-20H-4, 6.5-8cm, late Eocene zone E15. *Tenuitella angustiumblicata* **3a-3c**, IODP Sample 1411B 17H-3, 15-16.5cm, early Oligocene zone O1. *Dipsidripella danvillensis* **4a-4c**, IODP Sample 1411C 17H-5, 127-128.5cm, early Oligocene zone O1. *Chiloguembelina ototara* **5a-5c**, IODP Sample U1411-20H-4, 6.5-8cm, late Eocene zone E15. Scale bars: 100µm (whole specimens), 10µm (close-up images).

Appendix 2. Planktonic foraminifera count data:

Presented below is the planktonic foraminifera count data from the >180 assemblage. Data is presented in actual counts on species level.

>180 assemblage count data

Sample ID	Depth (mbsf)	<i>Catapsydrax unicavus</i>	<i>Dentaglobigerina</i> sp. 1	<i>Dentaglobigerina galavisi</i>	<i>Dentaglobigerina globularis</i>	<i>Dentaglobigerina pseudovenezuelana</i>	<i>Dentaglobigerina taci</i>	<i>Dentaglobigerina tapuriensis</i>	<i>Dentaglobigerina venezuelana</i>	<i>Globigerinatheka index</i>	<i>Globigerinatheka tropicalis</i>	<i>Globorotaloides eovariabilis</i>	<i>Globorotaloides quadrocameratus</i>	<i>Globorotaloides suteri</i>	<i>Globoturborotalita barbula</i>	<i>Globoturborotalita bassriverensis</i>	<i>Globoturborotalita cancellata</i>	<i>Globoturborotalita</i> sp. 1	<i>Globoturborotalita gnaucki</i>	<i>Globoturborotalita martini</i>	<i>Globoturborotalita ouachitaensis</i>	<i>Paragloborotalia griffinoidea</i>	<i>Paragloborotalia nana</i>
1411C 8H-2, 66.5-68	137.165	80		9	17			42	18			1	4	14					1		6	13	13
1411C 8H-2, 134.5-136	137.845	142						28	9			3	3	41				7	1	1	4	5	1
1411C 8H-3, 50.5-52	138.505	79		5	16			43	20					23		2		1			5	8	3
1411C 8H-3, 118.5-120	139.185	133		8	3			16	1				3	23		4	8	1	1	5	7	14	11
1411C 8H-4, 38.5-40	139.885	104		4			20	27	10				8	11		7	11	2			10	18	11
1411C 8H-4, 106.5-108	140.565	74			15		18	24	24			2	1	7		7	12		1	7	7	40	19
1411C 8H-5, 26.5-28	141.265	84		10	15		40	12	16					8		6	6	3			19	14	10
1411C 8H-5, 94.5-96	141.945	48		4	4		14	7	3				1	2		9	3	1			11	57	23
1411C 8H-6, 14.5-16	142.645	54		5	2		22	6	10					4		8	6	1		4	28	26	21
1411C 8H-6, 78.5-80	143.285	33		8	1	1	45	2	10				6	8		5	23	6			17	27	8
1411B 17H-2 95-96.5	145.550	158		5			8	6	3			1	6	22	1	9	24	1		2	5	6	
1411B 17H-3, 15-16.5	146.250	82	1	8	2		14		6				4	4		14	4			2	16	25	12
1411B17H38384.5	146.930	114		5	7		9	3	7			1	3	5	1	10	2	3		1	28	21	11
1411B 17H-4, 2.5-4	147.625	128		7	10	1	7	14	12				3	15		11	4			4	13	24	6
1411B 17H-4, 70.5-72	148.305	46	7	9	5	2	6		2				1	5		9				1	27	33	7
1411B 17H-4, 138.5-140	148.985	42	4	5	9		5		4			1	3	3		23		1	1	2	26	9	5

1411B 17H-5, 75-76.5	149.850	58	23	1		1		7					5	14	4	8	19	1		12	71	11	12
1411B 17H-5, 127-128.5	150.370	49	5	15	1	1			1				2	10		14	1				38	26	8
1411C 9H-3, 94.5-96	148.365	48	8	8	2	6			4			1	6	22		21	5			2	42	33	8
1411C 9H-4, 14.5-16	149.035	94	6	18	4	3	5		3				7	13		18	10			1	20	10	
1411C 9H-4, 82.5-84	149.715	40	5	16	5	10	3		6			1	1	7	5	33	10			2	48	17	10
1411C 9H-5, 6.5-8	150.405	52	28	6	6	4	3	2	8			2	3	11			12			4	5	13	8
1411C 9H-5, 74.5-76	151.085	24		3	12	5			3				2	5		1	5	1		2		34	16
1411B 18H-1, 22.5-24	152.825	71	1	10	11	1			15				2	39		2	10	4			2	34	16
1411B 18H-1, 90.5-92	153.505	47	16	29	5	1	9		2			1	7	34		4	16				2	7	3
1411B 18H-2, 10.5-12	154.205	47	2	18	12	1	13	12	7			2	7	19			14	2		2	5	25	2
1411B 18H-2, 78.5-80	154.885	54		14	6	4			13			2	7	18		2	20			1	4	14	1
1411B 18H-2, 146.5-148	155.565	66	1	27	17	8		1	6			1	5	22		11				5	17	23	9
1411B 18H-3.66-67.5	156.260	80		26	5	4		1	19			1	12	44		3	13			4	6	29	13
1411B 18H-3, 134-135.5	156.940	77	1	11	5	8	3		6				5	19		6	17			2	13	34	11
1411B 18H-4, 54.5-56	157.645	36		18	5	10		2	16			4	10	28		2	6				5	32	34
1411B 18H-4, 122.5-124	158.325	38		18	9	7						1	3	20					1	1	5	49	16
1411B 18H-5, 42.5-44	159.025	61	2	53	4	5			8			1	4	70		5	9				2	3	10
1411B 18H-5, 110.5-112	159.705	50	2	20	5	3							2	44			9		1	4	7	15	11
1411B 18H-6, 30.5-32	160.405	74		15									1	50		5	7			7	7	4	7
1411B 18H-6, 98.5-100	161.085	44		11								1	2	57	2	3	5	1		1	6	16	13
1411B 18H-7, 18.5-20	161.785	31	4	35										50		6	6	3		4	14	6	4
1411B 18H-7, 66.5-68	162.265	41	3	31		1							5	30	1	5	6	1	1	1	8	7	6
1411C 11X-1, 2.5-4	156.725	29	2	35		1				1		1		33		3					2	33	32
1411C 11X-1, 70.5-72	157.405	35		11								1		61		7		2			3	5	4
1411C 11X-1, 138.5-140	158.085	23		5									2	33		3					5	4	1
1411C 11X-2, 58.5-60	158.785	99	4	26	6	3	2					2	13	17		8	2			5	19	15	9
1411C 11X-2, 126.5-128	159.465	33		14		4								22		2					7	46	12
1411C 11X-3, 46.5-48	160.165	118		21	1	3			4					13		5		1		1	14	21	11
1411C 11X-3, 114.5-116	160.845	33	1	41		7							8	19				2				9	4

1411C 11X-4, 34.5-36	161.545	52		22		3							14							19	10
1411C 11X-4, 102.5-104	162.225	38	1									1	20		4			1		3	6
1411C 11X-5, 22.5-24	162.925	35		50		5					3	3	23		2		1		8	14	6
1411C 11X-5, 90.5-92	163.605	91		24		6					9	5	57		2	4			3	2	11
1411C 11X-6, 10.5-12	164.305	39		39		5							58							6	
1411B 19H-2, 98.5-100	164.585	128		8									47		4				3	8	4
1411B 19H-2, 142.5-144	165.025	31		21		2							45		5		1		1	6	34
1411B 19H-3, 62.5-64	165.725	12		17		2						2	42		3				1	12	54
1411B 19H-3, 130.5-132	166.405	26		16		2	3					1	1	45		6		2		3	2
1411B 19H-4, 50.5-52	167.105	11		9		2				12		1		57		11				1	7
1411B 19H-4, 118.5-120	167.785	31		2						1			1	10				1			1
1411B 19H-5, 38.5-40	168.485	44		12		1				5	1	1	3	31		3		6		2	
1411B 19H-5, 106.5-108	169.165	67		11						12			5	31		2		5		1	3
1411C 12X-1, 46.5-48	166.765	45		15		3				3		1		45		5		1		1	1
1411C 12X-1, 114.5-116	167.445	15		8		2				24	2		5	21		5		3		1	2
1411C 12X-2, 34.5-36	168.145	25		13						38		1		46		2				1	
1411C 12X-2, 102.5-104	168.825	15		12		1				75	3		2	49		4				2	1
1411C 12X-3, 26.5-28	169.565	36		17		8				12	8		7	53		2		3		6	4
1411C 12X-3, 94.5-96	170.245	22		7		7			1	21	8		5	42		7				3	5
1411C 12X-4, 14.5-16	170.945	54		24		3							7	10		1					3
1411C 12X-4, 82.5-84	171.625	40		14		2			3			1	2	30		7				2	3
1411C 12X-5, 2.5-4	172.325	40		15		14			1	1			9	33		4			1	1	5
1411C 12X-5, 70.5-72	173.005	44		41					1				5	37		4		1		3	2
1411C 12X-5, 138.5-140	173.685	38		21		1				1		1	1	25							1
1411C 12X-6, 58.5-60	174.385	27		30	2	5			5			1	9	35		5				7	7
1411B 20H-2, 106.5-108	174.165	34		28						1		1	3	40		6		2			1
1411B 20H-3, 26.5-28	174.865	15		12						44	23		2	29		7		7		8	6
1411B 20H-3, 94.5-96	175.545	40		7		2				12	5	4	16	45	1	16				8	19
1411B 20H-4, 82.5-84	176.925	37		23		16				2	1	4	10	43		5				7	8

Sample ID	Depth (mbsf)	<i>Cribohantkenina inflata</i>	<i>Hantkenina alabamensis</i>	<i>Hantkenina nangulansensis</i>	<i>Hantkenina primitiva</i>	<i>Pseudohastigerina micra</i>	<i>Pseudohastigerina naguewichiensis</i>	<i>Subbotina angiporoides</i>	<i>Subbotina corpulenta</i>	<i>Subbotina eocaena</i>	<i>Subbotina gortanii</i>	<i>Subbotina jacksonensis</i>	<i>Subbotina sp. 1</i>	<i>Subbotina utilisindex</i>	<i>Subbotina linaperta</i>	<i>Subbotina sp. 2</i>	<i>Subbotina yeguaensis</i>	<i>Turborotalia ampliapertura</i>	<i>Turborotalia cerroazulensis</i>	<i>Turborotalia cocoaensis</i>	<i>Turborotalia increbecens</i>	Other
1411C 8H-2, 66.5-68	137.165							1	9	5			1	22	13			25			7	
1411C 8H-2, 134.5-136	137.845								1	3				27	4			16			8	
1411C 8H-3, 50.5-52	138.505								3	8	6			12	7			46			11	1
1411C 8H-3, 118.5-120	139.185							7	6	8	1			21		1		9			5	1
1411C 8H-4, 38.5-40	139.885							1	2	11				9		1		19			2	6
1411C 8H-4, 106.5-108	140.565							2	3	7	1			5				18			5	1
1411C 8H-5, 26.5-28	141.265								10	2	2			7				24			9	3
1411C 8H-5, 94.5-96	141.945							7	10	20	4			13	3	6		35				
1411C 8H-6, 14.5-16	142.645							1	6	13	2			10				54			13	
1411C 8H-6, 78.5-80	143.285							2	12	11				11				40			14	2
1411B 17H-2 95-96.5	145.550							1	4	6				20		1		8			3	1
1411B 17H-3, 15-16.5	146.250							3	20	7	21			19		1		24			10	
1411B17H38384.5	146.930								26	6	4		4	10		1		14			3	1
1411B 17H-4, 2.5-4	147.625								15	1	5			7		5		6			3	
1411B 17H-4, 70.5-72	148.305							6	27	7	4			26		5		48			18	
1411B 17H-4, 138.5-140	148.985								34	16	7			23		2		42			26	12
1411B 17H-5, 75-76.5	149.850								14	7	2		3	23	6			5				
1411B 17H-5, 127-128.5	150.370								17	6	19		4	10		5		27			25	11
1411C 9H-3, 94.5-96	148.365								16	8	1			14		2		14			16	13
1411C 9H-4, 14.5-16	149.035	2		1					17	11	7		13	10		9		6			11	1
1411C 9H-4, 82.5-84	149.715					2			15	14	4		5	7		2		29			4	

1411C 9H-5, 6.5-8	150.405		3	1	1				30	12	6		13	14		6		26			13	8
1411C 9H-5, 74.5-76	151.085		1	2					17	5	2		1	1		3		35		2	15	5
1411B 18H-1, 22.5-24	152.825								24	7			1	8		3		16		3	17	3
1411B 18H-1, 90.5-92	153.505			1					30	19	3			8	13	6		21		1	15	
1411B 18H-2, 10.5-12	154.205								11	7	2			5		6		47		4	19	9
1411B 18H-2, 78.5-80	154.885								26	19	5		2	10				33			45	
1411B 18H-2, 146.5-148	155.565		1		1	1			23	11	3	5		3	4			6			13	3
1411B 18H-3.66-67.5	156.260					3			12	8	1			6	2		1	5			7	
1411B 18H-3, 134-135.5	156.940			1		4			8	3	1	30	12	16				28		2	7	
1411B 18H-4, 54.5-56	157.645		2	2	1	1			26	9	1			9			4	28			9	
1411B 18H-4, 122.5-124	158.325				1				31	21	1	17		5	3	2	2	30			16	3
1411B 18H-5, 42.5-44	159.025		1					2	14	8	1	12		4	7			11			2	1
1411B 18H-5, 110.5-112	159.705		1		5			1	19	5	1	5	3	2	3	3		48		2	25	4
1411B 18H-6, 30.5-32	160.405	1		3					38	2		15	20	2		2		18			16	6
1411B 18H-6, 98.5-100	161.085	1	1		1				12	4		4	1	6	15		3	12	1		14	2
1411B 18H-7, 18.5-20	161.785			2	2	1			39		5	10		3	9	3	19		16	15		1
1411B 18H-7, 66.5-68	162.265		2	1	2	2			41	2	4	11	23	1	3	3	19	1	9	22		1
1411C 11X-1, 2.5-4	156.725		1		3	3			24	15		22	13	6	7		12	8	2	7	5	
1411C 11X-1, 70.5-72	157.405				1	3		1	24	35		4	2	10	49		28	4	2	5	3	
1411C 11X-1, 138.5-140	158.085								7	13		2		12	12		14		2	6		1
1411C 11X-2, 58.5-60	158.785								14	4	1	17		18				5		9	1	
1411C 11X-2, 126.5-128	159.465			2	1	2			34	8	2	18	7	7	3		19	5	32	18		2
1411C 11X-3, 46.5-48	160.165		5		3			1	27	15	5		2	12				5	5	9		
1411C 11X-3, 114.5-116	160.845			1	1		1		33	22		16	17	6	6	2	20	2	10	13	4	
1411C 11X-4, 34.5-36	161.545					3			50	34		13	31	10	17		18	1	1		1	1
1411C 11X-4, 102.5-104	162.225							3	19	22		7		7	5		9	5			1	1
1411C 11X-5, 22.5-24	162.925					8			45	10	18	19	24	1	2		14	5			2	2
1411C 11X-5, 90.5-92	163.605							12	10	9	4	25	4	2	4		4		5	4		3
1411C 11X-6, 10.5-12	164.305								21	10	6	44	42	1	2	2		3	7	5		

1411B 19H-2, 98.5-100	164.585					2			20	17	2	7	2	6	16			9	9	7		
1411B 19H-2, 142.5-144	165.025								23	42	2	28		8	11	2	6	8	6	2	7	
1411B 19H-3, 62.5-64	165.725					2			11	41	3	29	19	6	18	1	1	2	1	4	2	
1411B 19H-3, 130.5-132	166.405								26	25		42	28	7	8	1	10	1	9	5		2
1411B 19H-4, 50.5-52	167.105					7			7	49	2	6	26	18	12		18	2	5	4	4	4
1411B 19H-4, 118.5-120	167.785								1					4	1							
1411B 19H-5, 38.5-40	168.485			2	1				12	6	2	4	8	2	10		3	8	4	3	1	
1411B 19H-5, 106.5-108	169.165					1			10	4		2	2	3	11		3	6	16	8	1	3
1411C 12X-1, 46.5-48	166.765								8	45	1	29	21	3	14	8		10	11	30	1	
1411C 12X-1, 114.5-116	167.445								4	31	2	18	12	9	6			2	16	13	1	3
1411C 12X-2, 34.5-36	168.145								2	28		12	10	11	36			6	2	10	1	4
1411C 12X-2, 102.5-104	168.825								8	19		9	20	9	49			11	3	2	4	1
1411C 12X-3, 26.5-28	169.565								2	36	1	2	25	14	32	1		16	7	5	3	
1411C 12X-3, 94.5-96	170.245	3	1						17	27			29	18	22			16	11	26	2	
1411C 12X-4, 14.5-16	170.945								6	6	2	14	3	9	8			6	5	12	3	
1411C 12X-4, 82.5-84	171.625	1	2			1			18	33	2		36	10	15	3		7	41	24	2	1
1411C 12X-5, 2.5-4	172.325					1			2	24	2		12	43	27	2		7	9	8	6	
1411C 12X-5, 70.5-72	173.005	3			1	4			12	11	5		14	24	9			40	10	5	19	1
1411C 12X-5, 138.5-140	173.685					1			6	4		2	2	15	10			12	1		6	
1411C 12X-6, 58.5-60	174.385					1			10	7	2		17	49	17			18	13	13	19	1
1411B 20H-2, 106.5-108	174.165								26	4	3	4	2	37	62		13	6	12	8	1	
1411B 20H-3, 26.5-28	174.865					6	1		11	13		8	6	31	51	2	10	10	2	1	1	1
1411B 20H-3, 94.5-96	175.545					14			7	8	2		15	45	20			1			3	10
1411B 20H-4, 82.5-84	176.925		2		4				6	2	7		17	38	15			20	9	11	7	

>63 assemblage count data

Sample ID	Depth (mbsf)	<i>Cassigerinella eocaenica</i>	<i>Cotpsyrax unicavus</i>	<i>Chiloguembelina otatara</i>	<i>Dentaglobigerina</i> sp. 1	<i>Dentaglobigerina galavisi</i>	<i>Dentaglobigerina globularis</i>	<i>Dentaglobigerina pseudovenezuelana</i>	<i>Dentaglobigerina taci</i>	<i>Dentaglobigerina tapuriensis</i>	<i>Dentaglobigerina venezuelana</i>	<i>Dipsidripella danvillensis</i>	<i>Globergerina officinalis</i>	<i>Globorotaloides eovariabilis</i>	<i>Globorotaloides quadricameratus</i>	<i>Globorotaloides suteri</i>	<i>Globoturborotalita barbula</i>	<i>Globoturborotalita bassriverensis</i>	<i>Globoturborotalita cancellata</i>	<i>Globoturborotalita</i> sp. 1	<i>Globoturborotalita gnaucki</i>	<i>Globoturborotalita martini</i>	<i>Globoturborotalita ouachitaensis</i>	<i>Streptochilus martini</i>
1411C 8H-2, 66.5-68	137.165		30	38	1					7	1	6	36	18		14	3				1	1	39	
1411C 8H-2, 134.5-136	137.845		52	12						1	2		3	65		12						2	9	
1411C 8H-3, 50.5-52	138.505		18	26			1			2		47	29	21		6	1	2		1		2	58	
1411C 8H-3, 118.5-120	139.185		40	33	1					2		1		49	2	31	2	2	2			4	20	
1411C 8H-4, 38.5-40	139.885		61	23			1		5	4	1	9		48	4	16		3		3	4		6	
1411C 8H-4, 106.5-108	140.565		23	26						2	5	58	7	11	2		1	9		3		8	47	
1411C 8H-5, 26.5-28	141.265		20	69			1		7	1		36	4	14		14		6	4	1		1	18	
1411C 8H-5, 94.5-96	141.945		11	47								47	5	10		10		6				3	30	
1411C 8H-6, 14.5-16	142.645		27	21								28	3	30		13		4	6	2		5	69	
1411C 8H-6, 78.5-80	143.285		25	29					1			34	5	21		7		13	9	8		1	71	1
1411B 17H-2 95-96.5	145.550		80	15								9	2	51		39		2	2	8			20	
1411B 17H-3, 15-16.5	146.250		17	82								8	30	12		16		6					13	
1411B17H38384.5	146.930		22	85					1			19	22	5	1	7		6	5	3		3	28	
1411B 17H-4, 2.5-4	147.625		31	15								4		14		16		1	2				4	
1411B 17H-4, 70.5-72	148.305		26	89	1	2						2	2	14	1	11		13		7			20	
1411B 17H-4, 138.5-140	148.985		14	46								13				1		9		4	1		57	
1411B 17H-5, 75-76.5	149.850		31	51		3						38	23	31	4	15		1		3		5	31	
1411B 17H-5, 127-128.5	150.370		27	38		1						11	15	16		19		18	1	1			28	
1411C 9H-3, 94.5-96	148.365		24	70									10	24	1	13		7		2	1	1	40	

1411C 9H-4, 14.5-16	149.035		43	37		2					1			21	3	15		23	1			1	37	
1411C 9H-4, 82.5-84	149.715		14	108		2						2	1	14		15		29			1		44	
1411C 9H-5, 6.5-8	150.405		26	85		2	1					2	24	15		4		13	9	1		6	43	
1411C 9H-5, 74.5-76	151.085		27	82					1				3	6		1		12		1		3	52	
1411B 18H-1, 22.5-24	152.825		81	39			1				2	1	5	21	6	14		17	2	3		2	6	
1411B 18H-1, 90.5-92	153.505		60	44	6	4							18	32	2	12		13	7	4		2	10	
1411B 18H-2, 10.5-12	154.205		25	65		1			3		1	4	17	18		11		2	2	4		1	47	
1411B 18H-2, 78.5-80	154.885		10	55		3						1		4		7		33		6		3	37	
1411B 18H-2, 146.5-148	155.565		11	98	1						1	3	29	8		15		6	8	3		6	28	
1411B 18H-3.66-67.5	156.260		28	84		6	2	2			2		30	9	4	18		15	1	2		4	12	
1411B 18H-3, 134-135.5	156.940		31	101		1							9	10	1	8		6		3		2	43	
1411B 18H-4, 54.5-56	157.645		9	157		2	1					2	1	5	1	19		17		1			6	
1411B 18H-4, 122.5-124	158.325		26	46			3					1	25	3	1	15		12	2	4		1	2	
1411B 18H-5, 42.5-44	159.025		92	10		7							10	19	4	75		5	1	7			4	
1411B 18H-5, 110.5-112	159.705		14	40		2						1	15	2		38		4	1	2			8	
1411B 18H-6, 30.5-32	160.405		14	58								3	9	7	1	26		10		1		2	10	
1411B 18H-6, 98.5-100	161.085	2	23	26								1	22	12		55	1	5	2	1		1	8	
1411B 18H-7, 18.5-20	161.785		23	39		5						2	32	9		37		17	5	8		3	18	
1411B 18H-7, 66.5-68	162.265	1	15	112		1						1	27			37		11	1	3			5	
1411C 11X-1, 2.5-4	156.725		12	53		5						2	43			35		30		6			4	
1411C 11X-1, 70.5-72	157.405	1	30	53								1	41	12		55		13		5			4	
1411C 11X-1, 138.5-140	158.085	1	30	41									47	7	5	52		13				3	2	
1411C 11X-2, 58.5-60	158.785	1	43	22		2						11	3	11	1	3		8				5	51	
1411C 11X-2, 126.5-128	159.465		18	54								1	38	1		32		12				1	2	
1411C 11X-3, 46.5-48	160.165		55	32								1	19	20	1	19		3		4			44	
1411C 11X-3, 114.5-116	160.845		8	60		2							20	16		47		8		1		3	2	
1411C 11X-4, 34.5-36	161.545	3	29	80								4	33	10		47		7				2	1	3
1411C 11X-4, 102.5-104	162.225	4	12	85								2	42	4		22		7				1		
1411C 11X-5, 22.5-24	162.925	2	10	47	1							8	14	9		24		12		4		5	7	

1411C 11X-5, 90.5-92	163.605	1	21	20		1						1	6	17	2	33		9		1				
1411C 11X-6, 10.5-12	164.305		18	66		1							21	10	3	45		6						
1411B 19H-2, 98.5-100	164.585		21	44								11		4	4	55		26		1		8	18	
1411B 19H-2, 142.5-144	165.025		5	163								5		4	1	31		17				3	7	
1411B 19H-3, 62.5-64	165.725		8	101										8	1	37		9		2			9	
1411B 19H-3, 130.5-132	166.405		14	34										16		37		22		1			9	
1411B 19H-4, 50.5-52	167.105	1	3	45								3		9		35		23				4	18	
1411B 19H-4, 118.5-120	167.785	1	166	17								1	9	6	2	29		5		3				
1411B 19H-5, 38.5-40	168.485		12	148	2							1	19	8		20		12				2	4	
1411B 19H-5, 106.5-108	169.165		14	77									15	10		40		13	1	1			2	
1411C 12X-1, 46.5-48	166.765		5	176										2	1	37		5		1		1	9	
1411C 12X-1, 114.5-116	167.445		5	175								3		5		26		29				2	5	
1411C 12X-2, 34.5-36	168.145	3	21	92		2						2		10	5	36		29				2	9	
1411C 12X-2, 102.5-104	168.825	1	13	38		4						3		7	9	44	1	33				5	33	
1411C 12X-3, 26.5-28	169.565		12	30		1								16	3	32		37		2		4	18	
1411C 12X-3, 94.5-96	170.245	1	24	39			2					2		9	7	45	1	20		1		3	9	
1411C 12X-4, 14.5-16	170.945		35	26		5	1					2	8	3	6	12		19		4			54	4
1411C 12X-4, 82.5-84	171.625	2	15	83		2						9		9	9	45		24		1		2	14	
1411C 12X-5, 2.5-4	172.325	2	16	92		1						23		7	8	40		15					11	
1411C 12X-5, 70.5-72	173.005	1	26	113		5						2		3	12	32		23				3	11	
1411C 12X-5, 138.5-140	173.685	2	24	88		1						10	20	10		48		12		2			2	2
1411C 12X-6, 58.5-60	174.385		20	68		5						9		14	13	39	1	16				3	15	
1411B 20H-2, 106.5-108	174.165	1	25	66		2						1	20	8	12	44		12				5	3	1
1411B 20H-3, 26.5-28	174.865	1	16	24		4						11	11	10	6	43		29		9		2	8	
1411B 20H-3, 94.5-96	175.545	4	29	66		2						2	2	15	16	31	1	18				8	22	
1411B 20H-4, 82.5-84	176.925	5	12	78		1						13		21	8	32		26				5	8	

Sample ID	Depth (mbsf)	<i>Paragloborotalia griffinoidea</i>	<i>Paragloborotalia nana</i>	<i>Pseudohastigerina micra</i>	<i>Pseudohastigerina naugewichensis</i>	<i>Subbotina angiporoides</i>	<i>Subbotina corpulenta</i>	<i>Subbotina eocaena</i>	<i>Subbotina gortanii</i>	<i>Subbotina jacksonensis</i>	<i>Subbotina</i> sp. 1	<i>Subbotina utilisindex</i>	<i>Subbotina linaperta</i>	<i>Subbotina</i> sp. 2	<i>Subbotina yeguaensis</i>	<i>Tenuitella angustumbilicata</i>	<i>Tenuitella gemma</i>	<i>Tenuitella munda</i>	<i>Turborotalia ampliapertura</i>	<i>Turborotalia cerroazulensis</i>	<i>Turborotalia cocoaensis</i>	<i>Turborotalia increbecens</i>	Other
1411C 8H-2, 66.5-68	137.165	3	2	8	7		1	1					2				80		3				
1411C 8H-2, 134.5-136	137.845	3	2	8	3			1	1			3					117		2				2
1411C 8H-3, 50.5-52	138.505	4		10	14			1				1					55		1				
1411C 8H-3, 118.5-120	139.185	10	4	5	6		1	1				4					73		3			1	2
1411C 8H-4, 38.5-40	139.885	10	6	6	9											5	73					3	
1411C 8H-4, 106.5-108	140.565	15		2	16												57		5			3	
1411C 8H-5, 26.5-28	141.265	3		4	2							2					89		3			1	
1411C 8H-5, 94.5-96	141.945	10	1	8	12							2					95		1				
1411C 8H-6, 14.5-16	142.645	9	3	7	22		1	2				3					34		11				
1411C 8H-6, 78.5-80	143.285	10	3	5	20		1					1	3				30		2				
1411B 17H-2 95-96.5	145.550	10	1		21								2				40						
1411B 17H-3, 15-16.5	146.250	3	1	3	9		1									5	89		3			2	
1411B17H38384.5	146.930	3	2	6	15												66		1				
1411B 17H-4, 2.5-4	147.625	6		2	18		1					1				4	178		2			1	
1411B 17H-4, 70.5-72	148.305	8		12	25		2	1	1			3					49		10			1	
1411B 17H-4, 138.5-140	148.985	11	4	9	10		2	1				3					94		2				1
1411B 17H-5, 75-76.5	149.850	4		13	7		1	2				2					33		2				
1411B 17H-5, 127-128.5	150.370	8	5	11	11		2	1	2			1					73		1			3	7
1411C 9H-3, 94.5-96	148.365	21		4	5							3					66		4			2	2
1411C 9H-4, 14.5-16	149.035	8	3	8	16		5	3				4					62		2			2	3
1411C 9H-4, 82.5-84	149.715	10	5	10	15		1	2	1		1						21					4	

1411C 9H-5, 6.5-8	150.405	11	5	5	15			1			1						25	1	3			2	
1411C 9H-5, 74.5-76	151.085	22	10	16	18				1				1				36		4		1		3
1411B 18H-1, 22.5-24	152.825	21	3	6	18		2	2				1					30		5			1	10
1411B 18H-1, 90.5-92	153.505	10	5	12	16		1	1				2	5	2			27		1			4	
1411B 18H-2, 10.5-12	154.205	9	1	5	10							2					63		6				4
1411B 18H-2, 78.5-80	154.885	19	6	18	30			1									36		6			5	
1411B 18H-2, 146.5-148	155.565	11	3	9	37		2										17		2			2	
1411B 18H-3.66-67.5	156.260	27	5	12	22		1					1					12		1				
1411B 18H-3, 134-135.5	156.940	17	4	19	23							3					17		2				
1411B 18H-4, 54.5-56	157.645	11	8	16	21		2					1					16		1			2	1
1411B 18H-4, 122.5-124	158.325	10		16	15		1					1	2				97		9				3
1411B 18H-5, 42.5-44	159.025		2	19	4		1	2				3	4				28	1					1
1411B 18H-5, 110.5-112	159.705		1	30	6	1		2		1							117		11			4	
1411B 18H-6, 30.5-32	160.405	2	2	24	9		2										116		2			2	
1411B 18H-6, 98.5-100	161.085	7		17	6							1	4				96		3		1	3	
1411B 18H-7, 18.5-20	161.785	2	7	38	5		3			3	2	2	1		1		30			2	6		
1411B 18H-7, 66.5-68	162.265		2	26	8		2						1				46	1					
1411C 11X-1, 2.5-4	156.725	4		39	4			1		1	2		1				53		3		1		1
1411C 11X-1, 70.5-72	157.405	1	1	40	14		2					2	7		1		16			1			
1411C 11X-1, 138.5-140	158.085			21	12			4				3	1				51			1	6		
1411C 11X-2, 58.5-60	158.785	3	11	21	5			1				1					95		4		1		1
1411C 11X-2, 126.5-128	159.465	3	1	16	8		3	1							1		104			1	3		
1411C 11X-3, 46.5-48	160.165	7	4	25	19		3	2									40					1	1
1411C 11X-3, 114.5-116	160.845	1	9	31	12		4	4		4			1		5		55		1		5		
1411C 11X-4, 34.5-36	161.545	3	5	40	1		2			2	2						24					2	
1411C 11X-4, 102.5-104	162.225		27	48	5			1					2				38						
1411C 11X-5, 22.5-24	162.925	3	7	37	11		2	6			2						88						1
1411C 11X-5, 90.5-92	163.605	1	11	24	1			1		2							145			1	2		
1411C 11X-6, 10.5-12	164.305		11	25	3			6		2	2			1			79				1		

1411B 19H-2, 98.5-100	164.585		17	19	3		3	6		1		2	2				53					1	
1411B 19H-2, 142.5-144	165.025		11	34	1			2	1								15						
1411B 19H-3, 62.5-64	165.725	17	10	30			1				1						64	1					
1411B 19H-3, 130.5-132	166.405	29		14	5			3		1		1	1				106	7					
1411B 19H-4, 50.5-52	167.105	23		21	6			5				1	1				92	7	1		2		
1411B 19H-4, 118.5-120	167.785	2	4	5	4			1				2	1				35					3	1
1411B 19H-5, 38.5-40	168.485	2	1	14	8								1				48					2	1
1411B 19H-5, 106.5-108	169.165		2	22	10			1	1								90	2			2	3	
1411C 12X-1, 46.5-48	166.765		15	16	2			2		1			1				22				1	1	1
1411C 12X-1, 114.5-116	167.445			17			1	10			1		1				10	9					1
1411C 12X-2, 34.5-36	168.145			12	6			11					9				45				2	1	1
1411C 12X-2, 102.5-104	168.825			37	7			11		1	2	4	7				18	3	1		5	2	11
1411C 12X-3, 26.5-28	169.565			40	7		1	11		2		3	8				69	4				1	
1411C 12X-3, 94.5-96	170.245			35				7			4	7	2				66	9		1	2	1	5
1411C 12X-4, 14.5-16	170.945	16	6	32	16		1					2					37		3	1	6	1	
1411C 12X-4, 82.5-84	171.625			33			2	6			3	2	3				25	2	1	3	2	3	
1411C 12X-5, 2.5-4	172.325			20				3				4	3				46	8		1			
1411C 12X-5, 70.5-72	173.005			32								2	1				31	1	1			1	
1411C 12X-5, 138.5-140	173.685		2	9	4							1	1				48	9				5	
1411C 12X-6, 58.5-60	174.385			31			1					8	2				34	8	5	1	3	4	
1411B 20H-2, 106.5-108	174.165		8	18	9		1	2		1		3	7				42	4	2		1	2	
1411B 20H-3, 26.5-28	174.865			19	8		2	1				5	22				62	1			1		10
1411B 20H-3, 94.5-96	175.545		3	10			1	1			1	3	4				56	5					
1411B 20H-4, 82.5-84	176.925		1	14			1				3	6	1				56	7	1				1