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Symbiont 'bleaching' in planktic foraminifera during the Middle Eocene Climatic Optimum

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ABSTRACT

Many genera of modern planktic foraminifera are adapted to nutrient-poor (oligotrophic) surface waters by hosting photosynthetic symbionts, but it is unknown how they will respond to future changes in surface–ocean temperature and acidity. Here we show that ca. 40 Ma, some fossil photosymbiont-bearing planktic foraminifera were temporarily 'bleached' of their symbionts coincident with transient global warming during the Middle Eocene Climatic Optimum (MECO). At Ocean Drilling Program (ODP) Sites 748 and 1051 (Southern Ocean and mid-latitude North Atlantic, respectively), the typically positive relationship between the size of photosymbiont-bearing planktic foraminifer tests and their carbon isotope ratios ($\delta^{13}C$) was temporarily reduced for ~100 k.y. during the peak of the MECO. At the same time, the typically photosymbiont-bearing planktic foraminifera *Acarinina* suffered transient reductions in test size and relative abundance, indicating ecological stress. The coincidence of minimum $\delta^{18}O$ values and reduction in test size–$\delta^{13}C$ gradients suggests a link between increased sea surface temperatures and bleaching during the MECO, although changes in pH and nutrient availability may also have played a role. Our findings show that host-photosymbiont interactions are not constant through geological time, with implications for both the evolution of trophic strategies in marine plankton and the reliability of geochemical proxy records generated from symbiont-bearing planktic foraminifera.

Keywords: Middle Eocene Climatic Optimum, bleaching, photosymbionts, planktic foraminifera, Ocean Drilling Program

INTRODUCTION

Photosymbiotic algae play a critical role in the nutrition, reproduction, calcification, growth, and longevity of their planktic foraminiferal hosts. Any changes in photosymbiont activity will therefore have a direct impact on the 'success' of the host taxon (Bé et al., 1982; Bijma et al., 1990; Caron et al., 1982; Hemleben et al., 1989). Symbionts modify the chemistry of a foraminifer's calcifying microenvironment, which impacts the elemental and isotopic ratios of test calcite and imparts characteristic geochemical signatures that are preserved in the sedimentary record (e.g., D'Hondt et al., 1994; Elderfield et al., 2002; Hönisch et al., 2003). There is evidence from the geological record that photosymbionts hosted by planktic foraminifera can be lost or their activity inhibited (i.e. 'bleaching'). For example, in the late middle Eocene, the gradual breakdown of the host–symbiont relationship over 2 m.y. is implicated in the extinction of the large acarininids and morozovelloidids (Wade, 2004; Wade et al., 2008). Furthermore, a rapid increase in surface ocean temperatures during the Paleocene-Eocene Thermal Maximum (PETM) appears to have caused the short-term (<40 k.y.) loss of symbionts from the surface-dwelling planktic foraminifera *Morozovella and Acarinina* (Norris, 2007). Yet there is considerable uncertainty regarding how common this loss of symbionts is in the geologic record and, consequently, the mechanism(s) responsible.

The Middle Eocene Climatic Optimum (MECO) was a transient global warming event at ca. 40 Ma that interrupted the long-term Eocene cooling trend (Fig. 1; Bohaty and Zachos, 2003; Sexton et al., 2006a; Bohaty et al., 2009; Edgar et al., 2010). It lasted for ~500 to 800 k.y. and was marked by gradual ocean warming of ~3 to 6 °C, with peak warmth lasting <100 k.y. (Bohaty et al., 2009; Bijl et al., 2010).

Here we use the established relationship between test size and $\delta^{13}C$ in fossil planktic foraminifera as a proxy for photosymbiont activity (Berger et al., 1978; D'Hondt and Zachos, 1993; D'Hondt et al., 1994; Norris, 1996; Pearson et al., 1993; Spero and Lea, 1993). Symbiotic algae preferentially utilize isotopically light carbon (^{12}C) during photosynthesis, leaving dissolved inorganic carbon (DIC) in the foraminifer calcifying microenvironment relatively enriched in ^{13}C. As foraminifera grow and host additional symbionts (or support higher photosymbiont activity), a characteristic increase in $\delta^{13}C$ with increasing test size occurs (Spero and DeNiro, 1987). Using this relationship, we investigate whether host–symbiont interactions were affected by the geologically abrupt environmental changes that accompanied the MECO.

MATERIALS AND METHODS

Planktic foraminifera were analyzed from Ocean Drilling Program (ODP) Site 1051 (Blake Nose Plateau, subtropical North Atlantic Ocean, 30º03’N 76º21’W) and ODP Site 748 (Kerguelen Plateau, Indian sector of the Southern Ocean, 58º26’S 78º58’E). Middle Eocene paleo-water depths at these sites were ~700–2000 m (Bohaty et al., 2009; Shipboard Scientific Party, 1998; Shipboard Scientific Party, 2004). Planktic foraminifera at both sites are characterized by ‘frosty’ preservation (sensu Sexton et al., 2006b) and show some evidence of recrystallization but are free of infilling. Age models follow Edgar et al. (2010).

Planktic foraminiferal $\delta^{13}C$ data were generated using monospecific separates of the known photosymbiont-bearing genera *Acarinina* (*A. praetopilensis* and *A. topilensis* at Site 1051 and *Acarinina primitiva* at Site 748 and *Morozovelloides crassatus* (e.g., Pearson et al., 1993; Norris, 1996; Wade et al., 2008). Specimens of the inferred symbiotic genus *Globigerinatheka* and the asymbiotic genus *Subbotina* were also analyzed. All samples were picked from restricted size fractions between 150 and 450 μm. Samples were cleaned by ultrasonication, and between 5 and 30 individuals (depending on availability) were analysed from each size fraction. Stable isotope values were determined using Europa GEO 20-20 (University of Southampton, UK) and VG Prism (University of California - Santa Cruz, USA) mass spectrometers equipped with automated carbonate preparation devices. Stable isotope results are reported relative to the Vienna PeeDee Belemnite (VPDB) standard with an external analytical precision of ±0.05‰. Relative abundance data were generated from sample splits of the >300 μm size fraction on ~400 individuals.

RESULTS

Pre- and post-MECO assemblages of *Acarinina, Globigerinatheka,* and *Morozovelloides* show a distinct increase in $\delta^{13}C$ values with increasing test size (Fig. 2A and C), consistent with a surface habitat and hosting dinoflagellate photosymbiosis akin to modern taxa (Pearson et al., 1993; Norris, 1996; Sexton et al., 2006c; Tables DR1-DR4 in the GSA Data Repository). To our knowledge, these are the first published *Globigerinatheka* test size-$\delta^{13}C$ data, and confirm the long-held view that this group was symbiotic. *Acarinina* and *Morozovelloides* specimens display the highest absolute $\delta^{13}C$ values in each of the samples, with *Globigerinatheka* offset to slightly lower $\delta^{13}C$ values (Fig. 2). However, *Acarinina* and *Globigerinatheka* test size-$\delta^{13}C$ gradients are higher at Site 1051 than at Site 748, which is likely a function of either reduced light conditions and/or temperatures at higher latitudes, lower Symbiont density, or different symbionts (Table DR3). In contrast, the subbotinids exhibit no size-related increase in $\delta^{13}C$ values at either of the sites investigated and have lower $\delta^{13}C$ values than other analyzed taxa, consistent with an asymbiotic ecology and thermocline habitat (Pearson et al., 1993; Norris, 1996; Sexton et al., 2006c). During the peak of the MECO at ca. 40 Ma, the positive test size–$\delta^{13}C$ trend in *Acarinina* is temporarily reduced at both study sites, and in *Globigerinatheka* at Site 748 only, resulting in test size–$\delta^{13}C$ gradients more similar to the asymbiotic genus *Subbotina*. In contrast, *Morozovelloides*, a thermophilic genus confined to (sub)tropical areas and present only at Site 1051, shows no significant gradient reduction during the MECO, but a low gradient prior to the event.

Acarinina are the dominant surface-dwelling taxa at Site 1051 during the pre- and ‘initial’ MECO (Fig. 3A). They subsequently decrease in relative abundance, reaching lowest abundance during the peak warming interval of the event coincident with their smallest maximum test size (Fig. 3A; Table DR5) and lowest test size-$\delta^{13}C$ gradients (Fig. 2B). In contrast, *Morozovelloides* and *Globigerinatheka* generally increase in relative abundance and maximum test size (Figs. 3B and C) during the event, with a decrease or little change in abundance or test size following the MECO.

DISCUSSION

Mechanisms for a reduction of test size-$\delta^{13}C$ gradients

A reduction and/or loss of the test size–$\delta^{13}C$ gradients in some photosymbiont-bearing foraminifera during the peak of the MECO may have resulted from (1) gametogenic or ontogenetic overprinting of the symbiont $\delta^{13}C$ signal, (2) a switch in the type of symbiont hosted, (3) an increase in the average habitat depth during later stages of ontogeny, and/or 4) a loss or inhibition of photosymbionts.

First, we do not consider increased inclusion of metabolic CO_2 during late ontogeny, or enhanced calcite precipitation during gametogenesis, as viable explanations for the reduced $\delta^{13}C$–size trends observed in the MECO at ODP Sites 1051 and 748. Modern culture and § experiments do not provide support for either hypothesis because metabolic activity is highest in juvenile specimens (<100 µm) and decreases during later growth stages (Berger et al., 1978). There is also little evidence for depth migration of acarininids during late ontogeny (e.g., D'Hondt et al., 1994; Norris, 1996) and the addition of gametogenic calcite, even in heavily calcified globigerinathekids, is insufficient to remove any existing test size–$\delta^{13}C$ trend (Fig. 2).

A second possibility is that the primary algal symbiont groups in planktic foraminifera changed during the MECO, affecting test size-–$\delta^{13}C$ relationships (e.g., dinoflagellates versus chrysophytes; Bornemann and Norris 2007). Modern foraminifera such as *Globigerinella siphonifera* that host chrysophyte symbionts have a much lower $\delta^{13}C$–size gradient than those hosting dinoflagellates, e.g., *Globigerinoides ruber* (Hemleben et al., 1989). Thus, if acarininids switched from hosting dinoflagellates to chrysophytes during the MECO, their test size–$\delta^{13}C$ relationship might be indistinguishable from asymbiotic taxa, even though they were still symbiont bearing. While modern data are sparse, there is no evidence to suggest that individual taxa switch their symbiont type during their life cycle or between succeeding generations (e.g., Hemleben, 1989, Gast and Caron, 1996), although modern foraminifera are flexible with regards to the genetic subgroups of dinoflagellate that they host (Shaked and de Vargas, 2006). However, if taxa remained symbiotic we might not expect any coincident change in species test size or relative abundance.

Third, coincident with environmental change during the MECO, mixed-layer-dwelling foraminifera may have temporarily occupied a deeper position in the water column during late stages of ontogeny. A deeper habitat would also directly inhibit symbiont activity via a reduction in irradiance levels (Spero and DeNiro, 1987; Spero and Lea, 1993; Spero et al., 1997). Thus, foraminifera may have either passively or actively lost their symbionts and migrated to deeper waters to predate on the more abundant algae in the deep chlorophyll maximum. This scenario is analogous to events proposed for the PETM, when tropical 'excursion' taxa *M. allisonenesis* and *A. sibaiyensis* are thought to have occupied a deeper ecological niche, more similar to *Subbotina* (Kelly et al., 1996) and yield low $\delta^{13}C$–size gradients consistent with asymbiotic or chrysophyte-bearing planktic foraminifera (Kelly et al., 1998; Bornemann and Norris, 2007). Although changes in calcification depth of planktic foraminifera are not unprecedented on long (geological) time scales (e.g., Coxall et al., 2007), available $\delta^{18}O$ data for the MECO are ambiguous in this regard (Fig. DR1).

However, $\delta^{13}C$ data indicate maintenance of the offset between mixed-layer and thermocline taxa throughout the MECO, suggesting continued separation of depth habitats between taxa.

Fourth, a decrease in symbiont activity and/or symbiont concentration could explain the absence of a positive test size–$\delta^{13}C$ trend in typically symbiont-hosting foraminifera. Laboratory experiments show that the artificial removal of dinoflagellate symbionts from modern foraminifera species (simulating 'bleaching') is accompanied by decreases in test size (Bé et al., 1982; Caron et al., 1982), presumably owing to the ecological stress imposed by symbiont eradication. Similarly, the loss of symbionts from *Morozovelloides* in the late middle Eocene is coincident with a decrease in maximum test size (Wade and Olsson, 2009). Hence, the disappearance during the MECO of the normally positive test size–$\delta^{13}C$ trend in *Acarinina* and the associated pronounced decreases in their size and abundance is consistent with loss of their photosymbionts (Fig. 3C).

Bleaching mechanisms

Studies of modern marine taxa in stressed environments may provide some insight into the foraminiferal response to the MECO. However, direct analogy to bleaching events observed in modern coral and benthic foraminifera in the natural environment, and simulated in laboratory cultures is limited, owing to (1) different habitats (planktic versus benthic), (2) the likelihood that culture experiments are not directly representative of the natural environment, and (3) the different relative time scales (annual versus millennial) and number of generations involved. Furthermore, planktic foraminifera cannot be readily observed in situ; thus, we do not know if there have been detrimental losses of photosymbionts in response to modern environmental change.

If symbiosis is obligate in acarininids (as implied by analogy to modern taxa), bleaching is most likely not a direct stress response given the timescales of environmental change during the MECO. But perhaps cumulatively, environmental changes may have crossed a threshold beyond which foraminifer or their symbionts were unable to successfully operate, triggering the breakdown of the symbiotic relationship. The variable response of the three genera investigated here highlights differential relative sensitivities to the same environmental changes occurring during the MECO. The acarininids were the most sensitive genus to environmental changes, perhaps implying that they were living close to their environmental limits.

It is compelling that reduced test size-$\delta^{13}C$ gradients at both study sites (Fig. 3) occur within the short-lived interval of peak warmth (Figs 1 and 2); yet surface waters also experienced increased nutrient availability (Luciani et al., 2010; Witkowski et al., 2012) and an inferred pH reduction across the MECO (Bijl et al., 2010). However, it's unclear how changes in the trophic state relate to warming; the responses of marine organisms to ΔpH are variable (Hofmann et al., 2010) and culture experiments assessing the impact of carbonate chemistry on the $\delta^{13}C$ of planktic foraminiferal calcite appear to show little impact on the host-symbiont relationship (Spero et al., 1997). Consequently, while nutrient and pH changes may have exacerbated environmental stress, the temperature increase across the MECO was most likely the primary factor leading to the inhibition of photosymbiosis in *Acarinina* on a global scale. Regardless of the environmental control on foraminiferal bleaching during the MECO, all affected taxa were able to live and maintain populations, implying that, at least on geological short timescales, symbiosis is not essential to their survival. There are several modern mixed-layer taxa that do not harbour symbionts, e.g., *Globigerina bulloides* (Hemleben et al., 1989), indicating that symbionts are not essential for survival in the mixed layer.

If symbiosis is not essential for foraminifer survival, the exclusion of photosymbionts may represent an adaptive response to changing environmental and/or biotic pressures. Indeed, bleaching has been suggested to be an adaptive mechanism in corals allowing them to be recolonized by new types of algae better suited to short-lived conditions of environmental stress (Brown, 1997). Moreover, symbiont loss in *Acarinina* may have been passive: an indirect consequence of migration to a slightly deeper (i.e. aphotic) depth habitat during the MECO. Yet regardless of whether the loss or inhibition of symbionts was an adaptive or passive mechanism, it came at a cost, highlighted by the fact that *Acarinina* declined in size and abundance across the MECO compared with the other major surface-dwelling planktic foraminiferal groups (Fig. 3). The rapid recovery of test size-$\delta^{13}C$ gradients (and abundance and test size) to pre-event values following the MECO indicates that, once environmental conditions became more favourable for these planktic foraminifers or their symbionts, the photosymbiotic relationship was re-established at pre-event levels.

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FIGURE CAPTIONS

Figure 1**.** Benthic foraminiferal stable isotope records across the Middle Eocene Climatic Optimum (MECO) from Ocean Drilling Program Sites 1051 (Edgar et al., 2010), 738 and 748 (Bohaty and Zachos, 2003; Bohaty et al., 2009). Isotope stratigraphies at Sites 738 and 748 are aligned to Site 1051. Subdivisions indicate different climatic phases of the MECO.

Figure 2. Trends in $\delta^{13}C$ versus mean sieve size related trends in planktic foraminifera for Ocean Drilling Program (ODP) Sites 1051 and 748 across the Middle Eocene Climatic Optimum (MECO). Acar. = *Acarinina* spp (solid diamonds); Glob. = *Globigerinatheka* spp (open circles); Moro. = *Morozovelloides crassatus* (solid triangles) and Subb. = *Subbotina* spp (solid squares). Different coloured symbols from different samples.

Figure 3. Relative abundance changes in >300 µm-sieve size fraction (lines) and changes in maximum test size diameter (solid symbols) of the dominant surface-dwelling planktic foraminifera across the Middle Eocene Climatic Optimum (MECO) at Ocean Drilling Program Site 1051. Mean diameter of the 20 (where possible) largest specimens in each group is shown and plotted with 1σ.

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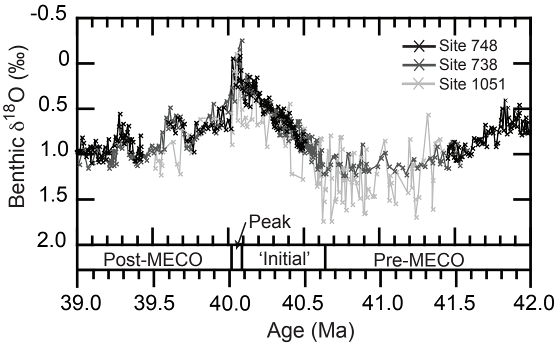
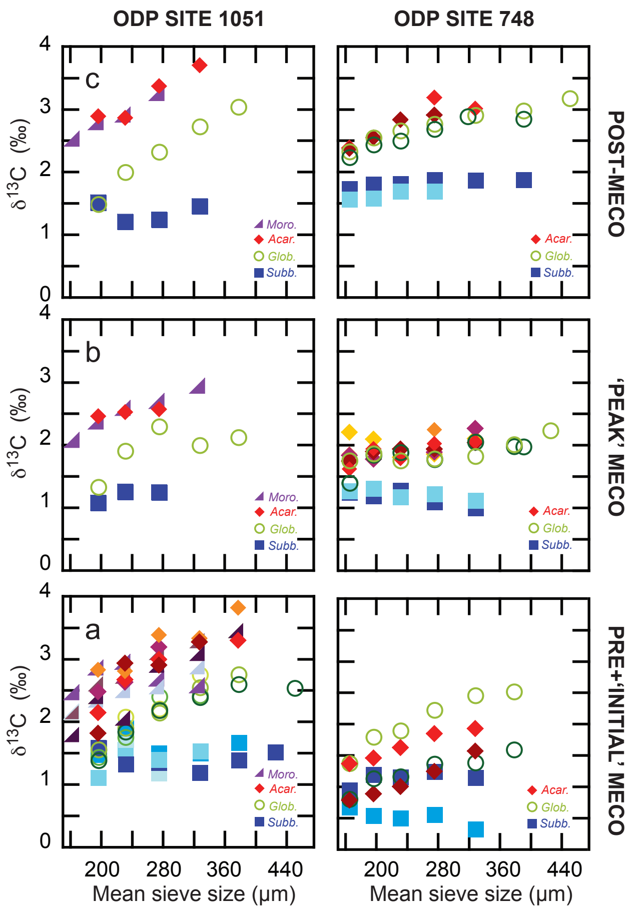
[1]GSA Data Repository item 2013002, stable isotope, test size data, and SEM images; Figure DR1-DR4; and Tables DR1-5, is available online at

www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

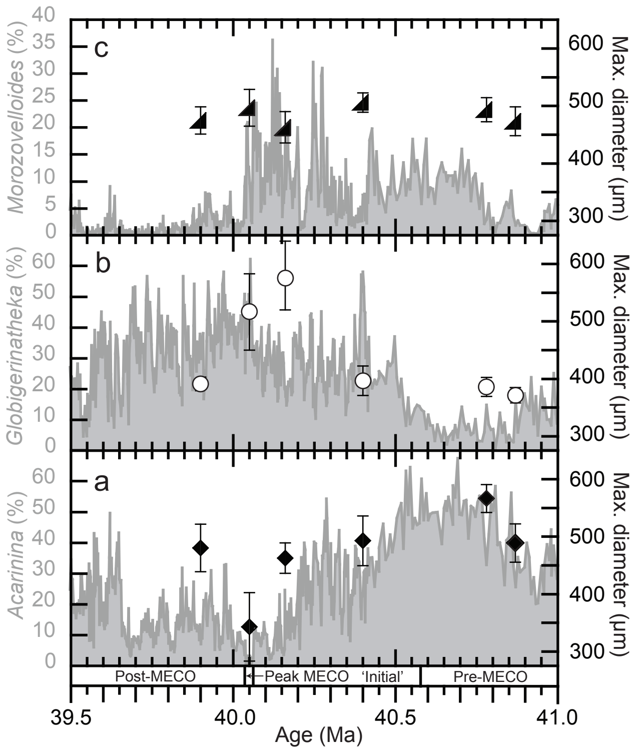
Edgar_Figure 1



Edgar_Figure 2

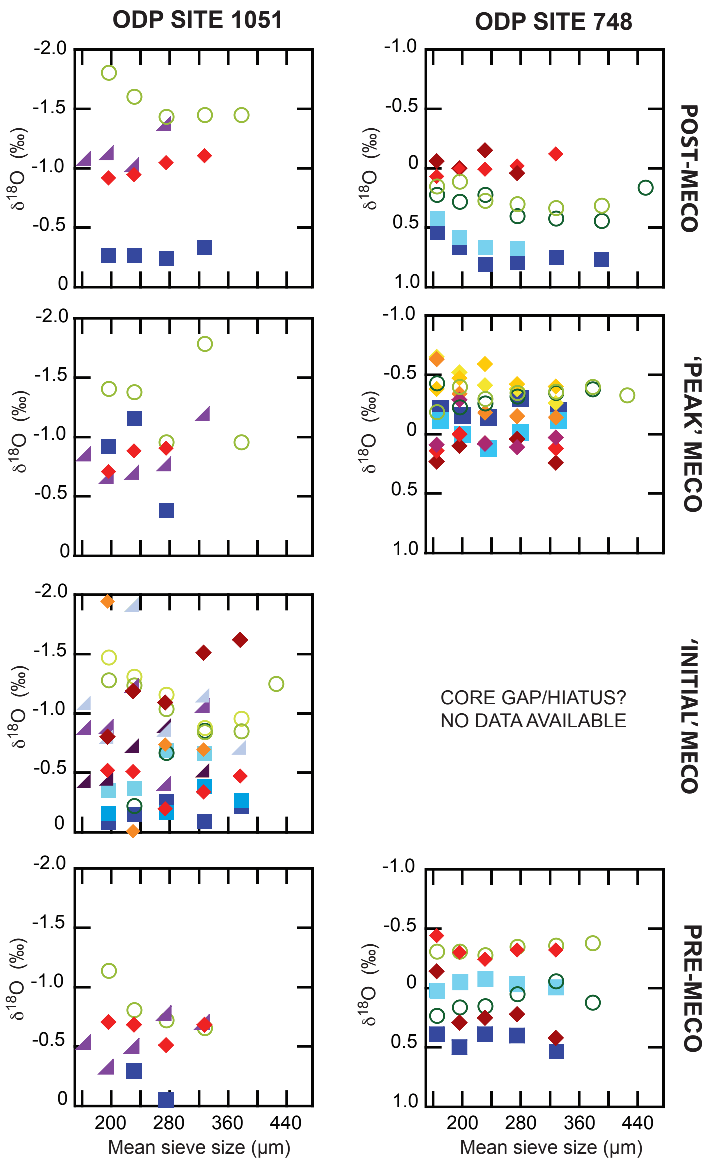


Edgar_Figure 3

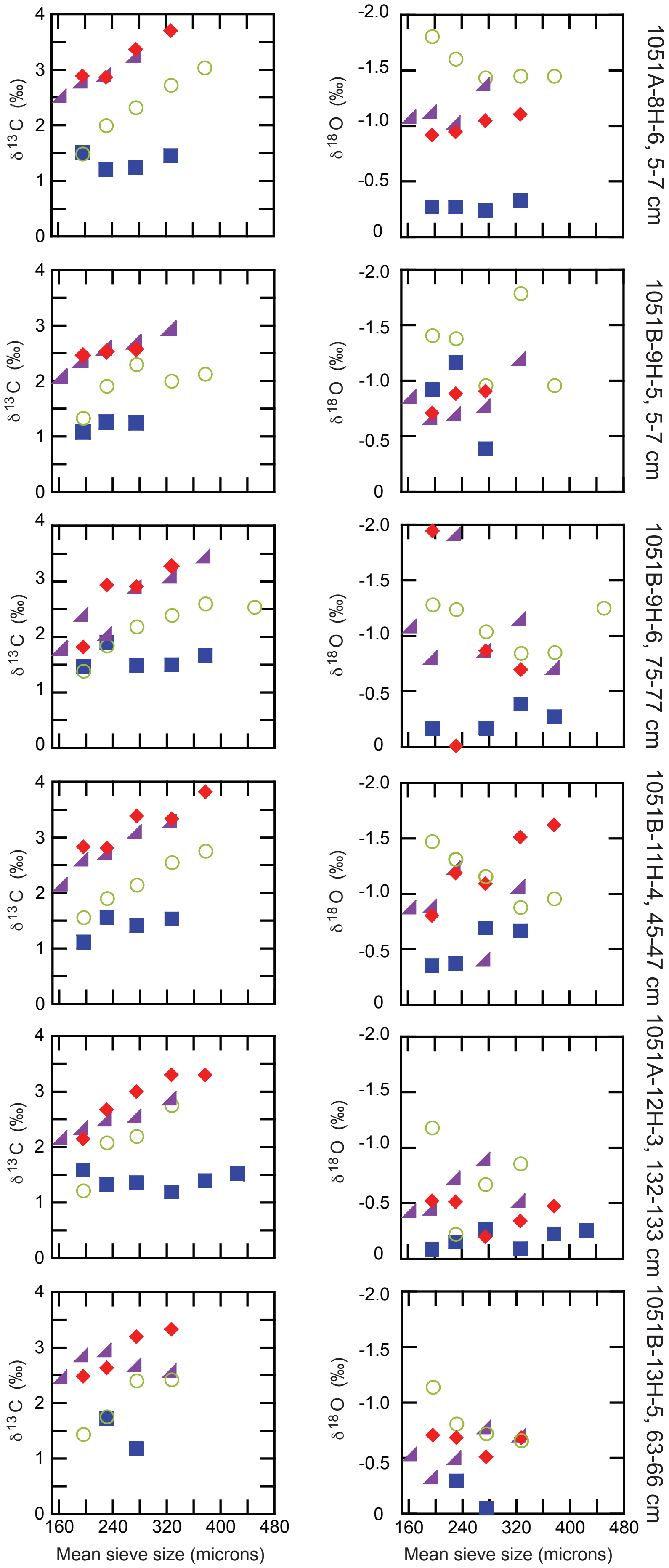


Data Repository Material: Symbiont 'bleaching' in planktic foraminifera during the Middle Eocene Climatic Optimum by Edgar et al.

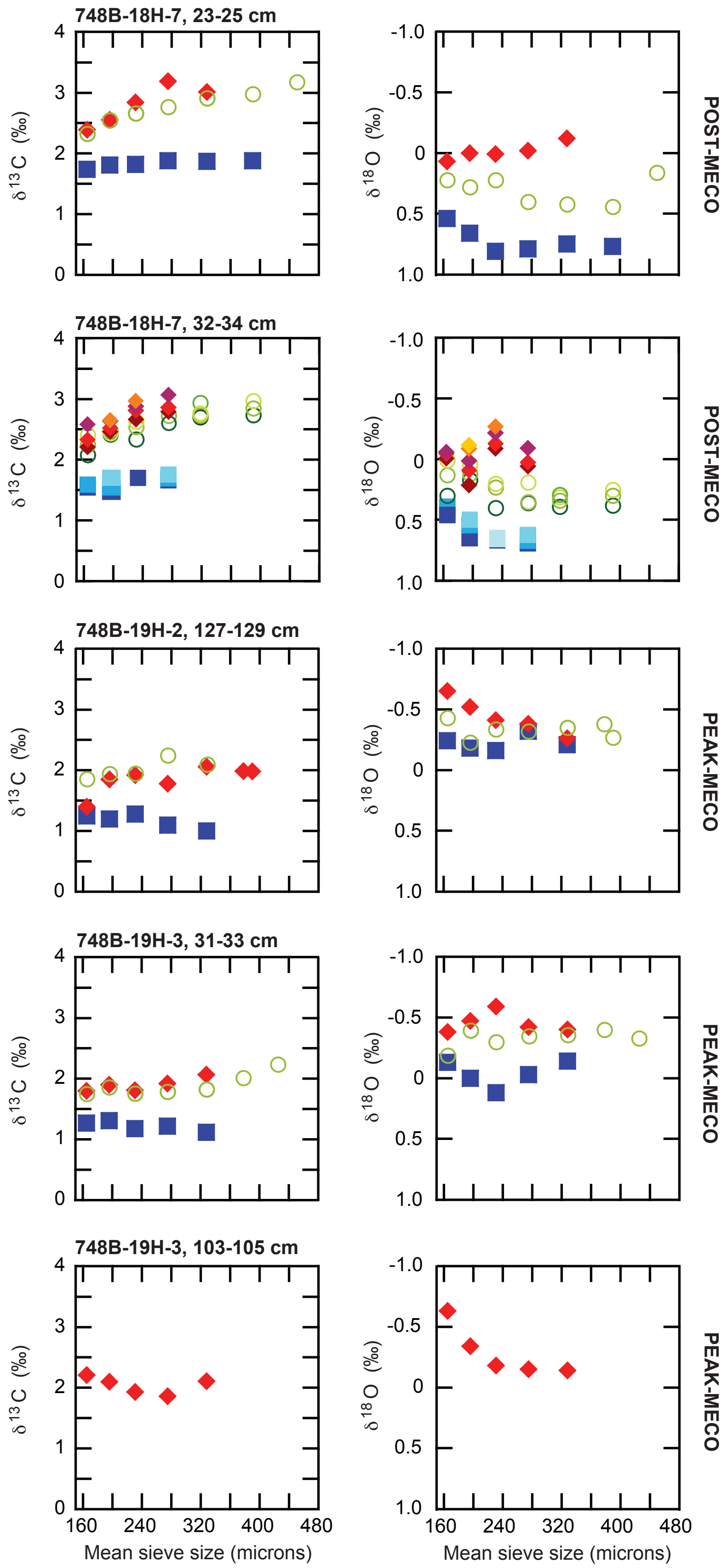
Data Repository Figure 1. $\delta^{18}O$ versus mean sieve size trends in planktic foraminifera at ODP Sites 1051 and 748 across the MECO. Abbreviations and symbols are: Acar. = *Acarinina* spp (solid diamonds); Glob. = *Globigerinatheka* spp (open circles); Moro. = *Morozovelloides crassatus* (solid triangles) and Subb. = *Subbotina* spp (soild squares). Different coloured symbols of the same shape are from different samples. For clarity, individual samples are plotted in Figs DR2 and DR3. $\delta^{18}O$-size related trends are shown for four different timeslices (rather than three as in Fig. 2) to distinguish between pre- and initial-MECO conditions. At Site 748, there is a clear offset in absolute $\delta^{18}O$ values between inferred surface (*Acarinina* and *Globigerinatheka*) and thermocline dwelling taxa (*Subbotina*) across the MECO providing little support for *Acarinina* or *Globigerinatheka* occupying a deeper position in the water column during the MECO. At Site 1051, it is more difficult to assess any changes in the relative depth ordering of taxa across the MECO. Perhaps, in part, becuase of the multiple species of *Globigerinatheka* and *Subbotina* combined for isotope analysis but also because of potential diagenetic alteration of $\delta^{18}O$ isotope values at this site. [Site 748 planktic foraminifer are likely less suseptible to diagenetic alteration becuase of weaker vertical thermal water column gradients at higher latitudes]. We note that $\delta^{13}C$ values are more resiliant to diagenetic alteration than $\delta^{18}O$ values and there is little difference in values reported between 'glassy' and 'frosty' planktic foraminifer (e.g., Pearson et al., 2001; Sexton et al., 2006). The overall reduced $\delta^{18}O$ offsets between taxa and lower test size-$\delta^{18}O$ gradients at Site 748 than at Site 1051 are most easily explained by the presence of a less thermally stratified water column at high latitude. Note the different y-axis values between ODP Sites 1051 and 748.

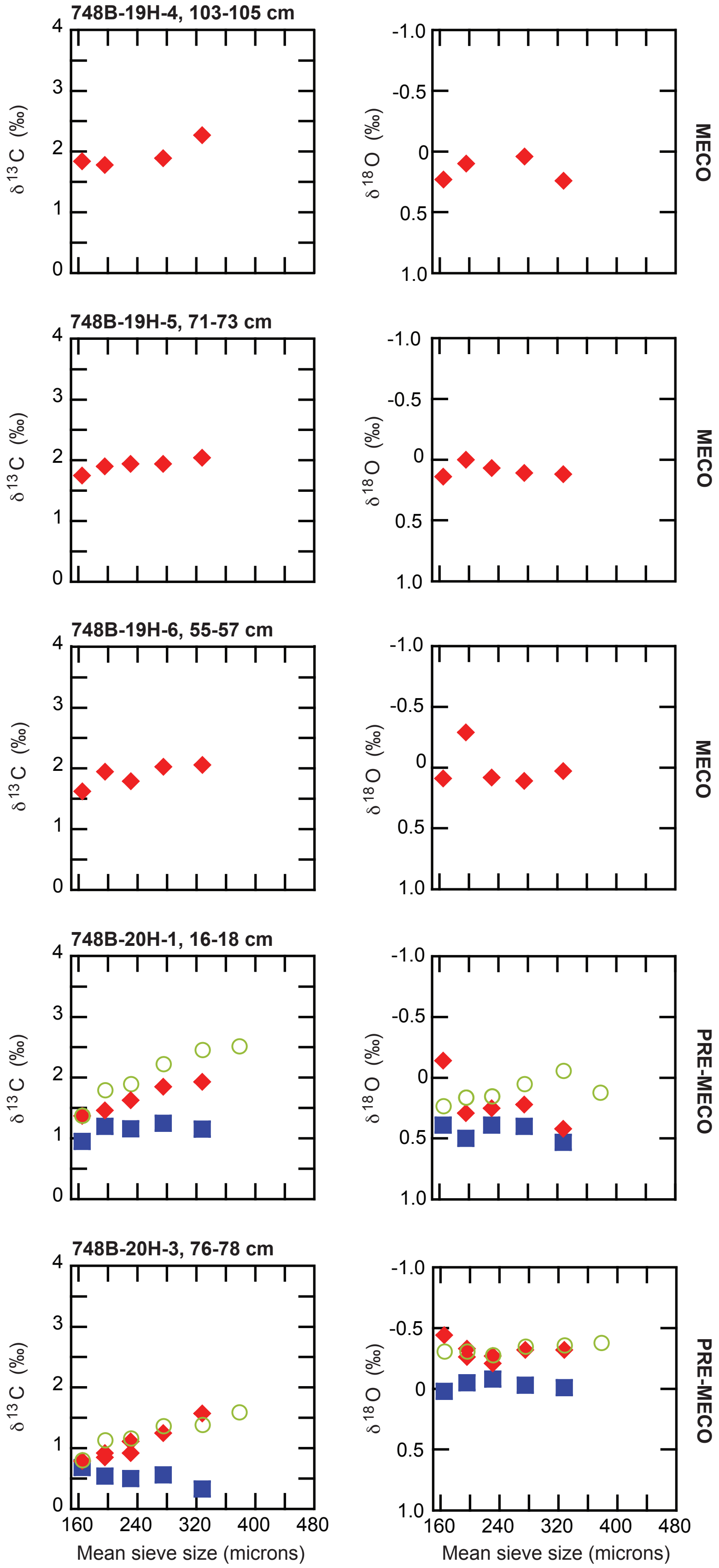


Data Repository Figure 2. δ13C and δ18O-mean sieve size related trends in planktic foraminifera in individual samples at ODP Site 1051 across the MECO. Different coloured symbols represent different genera of planktic foraminifera: *Acarinina topilensis* = solid red diamonds; *Morozovelloides crassatus* = solid purple triangles; *Globigerinatheka* spp = open green circles and *Subbotina* spp = solid blue squares. The globigerinathekids typically show a negative sieve size-δ18O gradient reflecting as they sink through the water column towards the end of their life cycle and precipitate a thick clacite crust (gametogenic calcite) from water with more positive δ18O values than the surface waters that they originally precipiated their test from.



Data Repository Figure 3. δ13C and δ18O-mean sieve size related trends in planktic foraminifera in individual samples at ODP Site 748 across the MECO. Different coloured symbols represent different planktic foraminifera: *Acarinina primitiva* = solid diamonds; *Globigerinatheka index* = open circles and *Subbotina* spp = solid squares.





748B-19H-4, 103-105 cm
748B-19H-5, 71-73 cm
748B-19H-6, 55-57 cm
748B-20H-1, 16-18 cm
748B-20H-3, 76-78 cm
δ 13 C (‰)
δ 18 O (‰)
MECO
PRE-MECO
Mean sieve size (microns)

Data Repository Figure 4 - Scanning electron microscope images from ODP Sites 1051 and 748 illustrating species concepts adopted in this study. Planktic foraminifera are ‘frosty’ not ‘glassy’ indicating some diagenetic alteration but are free of infilling. Scale bars are 100 µm in a-h and 10 µm in i. a. *Acarinina primitiva*, Sample 748B 19H-2, 127-129 cm. b and c. *Globigerinatheka index*, Sample 748B 19H-2, 127-129 cm. d. *Morozovelloides crassatus*, Sample 1051B 8H-6, 5-7 cm. e and f. *Acarinina topilensis*, Sample 1051B 8H-6, 5-7 cm. g and h. *Acarinina praetopilensis*, Sample 1051B 8H-6, 5-7 cm. i. close up of *A. topilensis* wall texture, Sample 1051B 8H-6, 5-7 cm. *A. topilensis* sensu stricto (e) is restricted to large size fractions, thus in this study we have adopted a broad species concept for *A. topilensis* that includes less elaborate morphological forms that fall within *A. praetopilensis*.

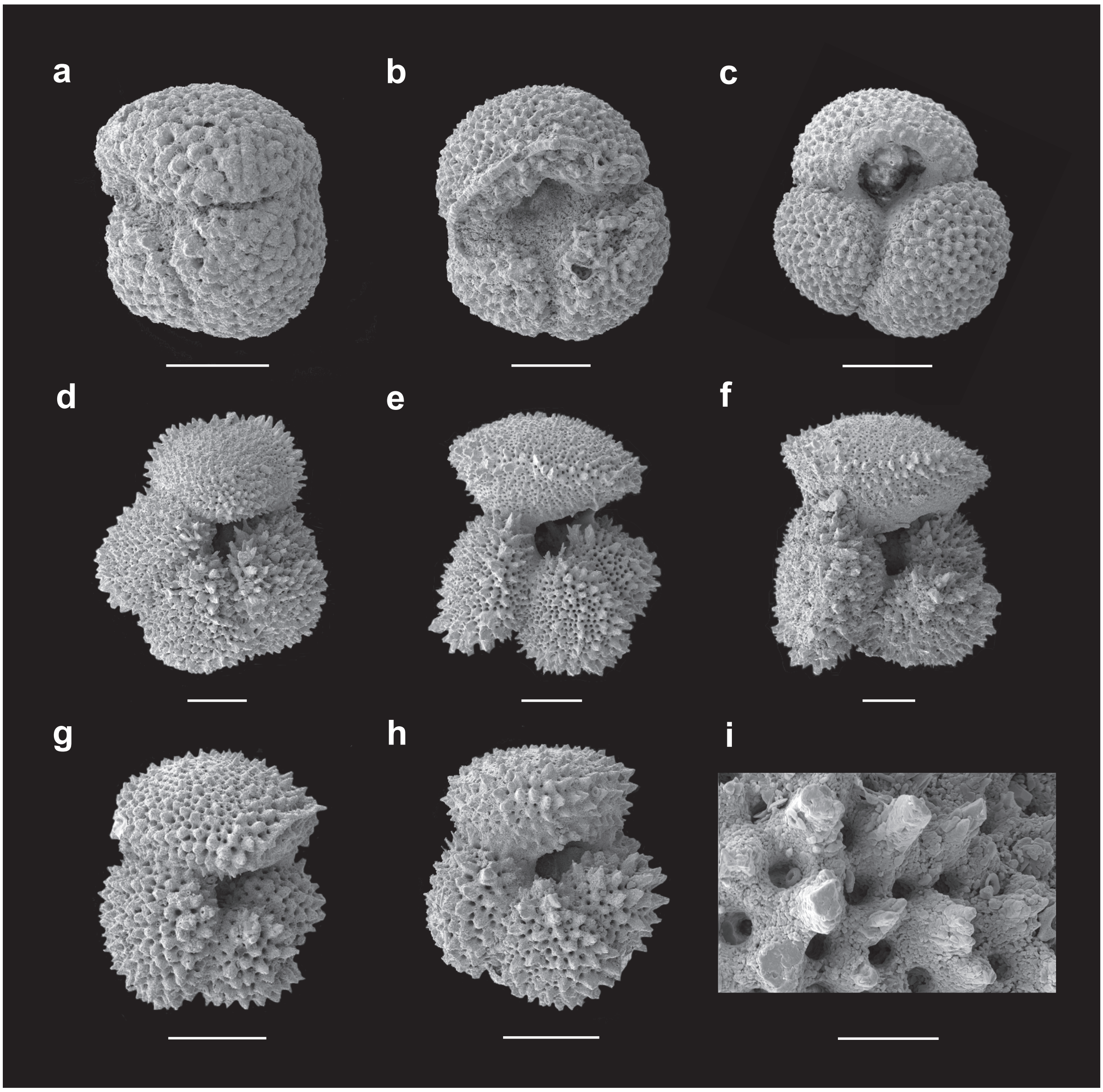


TABLE DR1. PLANKTIC FORAMINIFERAL SIZE FRACTION-$\delta^{13}C$ AND $\delta^{18}O$ DATA FROM ODP SITE 1051

Sample	**Depth (mbsf)**	**CK95* Age (Ma)**	**Taxon †**	**Sieve size fraction (microns)**	**$\delta^{13}C$ VPDB**	**$\delta^{18}O$ VPDB**
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	300-355	**3.704**	**-1.104**
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	250-300	**3.370**	**-1.046**
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	212-250	**2.865**	**-0.946**
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	180-212	**2.891**	**-0.919**
1051A-8H-6, 5-7 cm	69.14	39.90	*Morozovelloides crassatus*	250-300	**3.261**	**-1.379**
1051A-8H-6, 5-7 cm	69.14	39.90	*Morozovelloides crassatus*	212-250	**2.915**	**-1.030**
1051A-8H-6, 5-7 cm	69.14	39.90	*Morozovelloides crassatus*	180-212	**2.794**	**-1.130**
1051A-8H-6, 5-7 cm	69.14	39.90	*Morozovelloides crassatus*	150-180	**2.532**	**-1.082**
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	355-400	**3.043**	**-1.452**
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	300-355	**2.731**	**-1.451**
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	250-300	**2.324**	**-1.435**
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	212-250	**2.002**	**-1.604**
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	180-212	**1.489**	**-1.807**
1051A-8H-6, 5-7 cm	69.14	39.90	*Subbotina* spp	300-355	**1.455**	**-0.333**
1051A-8H-6, 5-7 cm	69.14	39.90	*Subbotina* spp	250-300	**1.243**	**-0.241**
1051A-8H-6, 5-7 cm	69.14	39.90	*Subbotina* spp	212-250	**1.205**	**-0.273**
1051A-8H-6, 5-7 cm	69.14	39.90	*Subbotina* spp	180-212	**1.515**	**-0.271**
1051B-9H-5, 5-7 cm	77.35	40.05	*Acarinina topilensis*	250-300	**2.573**	**-0.907**
1051B-9H-5, 5-7 cm	77.35	40.05	*Acarinina topilensis*	212-250	**2.528**	**-0.882**
1051B-9H-5, 5-7 cm	77.35	40.05	*Acarinina topilensis*	180-212	**2.459**	**-0.708**
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	300-355	**2.948**	**-1.197**
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	250-300	**2.704**	**-0.775**
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	212-250	**2.590**	**-0.702**
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	180-212	**2.374**	**-0.668**
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	150-180	**2.080**	**-0.858**
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	355-400	**2.130**	**-0.959**
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	300-355	**2.004**	**-1.786**
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	250-300	**2.299**	**-0.959**
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	212-250	**1.911**	**-1.380**
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	180-212	**1.335**	**-1.407**
1051B-9H-5, 5-7 cm	77.35	40.05	*Subbotina* spp	250-300	**1.248**	**-0.388**
1051B-9H-5, 5-7 cm	77.35	40.05	*Subbotina* spp	212-250	**1.263**	**-1.163**
1051B-9H-5, 5-7 cm	77.35	40.05	*Subbotina* spp	180-212	**1.080**	**-0.923**
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	300-355	**3.276**	**-0.697**
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	250-300	**2.922**	**-0.740**
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	212-250	**2.936**	**-0.010**
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	180-212	**1.821**	**-1.944**
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	400-450	**3.458**	**-0.713**
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	355-400	**3.095**	**-1.152**
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	250-300	**2.904**	**-0.865**
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	212-250	**2.062**	**-1.914**
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	180-212	**2.404**	**-0.803**
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	150-180	**1.797**	**-1.086**
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	400-450	**2.543**	**-1.251**
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	355-400	**2.604**	**-0.853**
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	300-355	**2.398**	**-0.844**
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	250-300	**2.187**	**-1.041**
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	212-250	**1.847**	**-1.238**
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	180-212	**1.392**	**-1.283**
1051B-9H-6, 75-77 cm	79.47	40.16	*Subbotina* spp	355-400	**1.670**	**-0.273**
1051B-9H-6, 75-77 cm	79.47	40.16	*Subbotina* spp	300-355	**1.499**	**-0.385**
1051B-9H-6, 75-77 cm	79.47	40.16	*Subbotina* spp	250-300	**1.490**	**-0.170**
1051B-9H-6, 75-77 cm	79.47	40.16	*Subbotina* spp	212-250	**1.909**	**0.308**
1051B-9H-6, 75-77 cm	79.47	40.16	*Subbotina* spp	180-212	**1.480**	**-0.165**

1051B-11H-4, 45-47 cm	92.25	40.4	*Acarinina topilensis*	355-400	**3.821**	**-1.621**
1051B-11H-4, 45-47 cm	92.25	40.4	*Acarinina topilensis*	300-355	**3.332**	**-1.512**
1051B-11H-4, 45-47 cm	92.25	40.4	*Acarinina topilensis*	250-300	**3.384**	**-1.093**
1051B-11H-4, 45-47 cm	92.25	40.4	*Acarinina topilensis*	212-250	**2.808**	**-1.187**
1051B-11H-4, 45-47 cm	92.25	40.4	*Acarinina topilensis*	180-212	**2.831**	**-0.805**
1051B-11H-4, 45-47 cm	92.25	40.40	*Morozovelloides crassatus*	300-355	**3.294**	**-1.066**
1051B-11H-4, 45-47 cm	92.25	40.40	*Morozovelloides crassatus*	250-300	**3.104**	**-0.410**
1051B-11H-4, 45-47 cm	92.25	40.40	*Morozovelloides crassatus*	212-250	**2.730**	**-1.234**
1051B-11H-4, 45-47 cm	92.25	40.40	*Morozovelloides crassatus*	180-212	**2.607**	**-0.891**
1051B-11H-4, 45-47 cm	92.25	40.40	*Morozovelloides crassatus*	150-180	**2.158**	**-0.880**
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	355-400	**2.762**	**-0.958**
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	300-355	**2.554**	**-0.880**
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	250-300	**2.151**	**-1.160**
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	212-250	**1.905**	**-1.312**
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	180-212	**1.562**	**-1.473**
1051B-11H-4, 45-47 cm	92.25	40.40	*Subbotina* spp	300-355	**1.535**	**-0.669**
1051B-11H-4, 45-47 cm	92.25	40.40	*Subbotina* spp	250-300	**1.407**	**-0.693**
1051B-11H-4, 45-47 cm	92.25	40.40	*Subbotina* spp	212-250	**1.562**	**-0.373**
1051B-11H-4, 45-47 cm	92.25	40.40	*Subbotina* spp	180-212	**1.117**	**-0.352**
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	355-400	**3.299**	**-0.472**
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	300-355	**3.299**	**-0.340**
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	250-300	**2.994**	**-0.200**
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	212-250	**2.675**	**-0.511**
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	180-212	**2.152**	**-0.521**
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	300-355	**2.880**	**-0.521**
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	250-300	**2.562**	**-0.899**
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	212-250	**2.504**	**-0.728**
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	180-212	**2.349**	**-0.453**
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	150-180	**2.174**	**-0.430**
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	300-355	**2.754**	**-0.859**
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	250-300	**2.200**	**-0.671**
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	212-250	**2.079**	**-0.225**
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	180-212	**1.218**	**-1.182**
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Subbotina* spp	400-450	**1.524**	**-0.254**
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Subbotina* spp	355-400	**1.393**	**-0.223**
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Subbotina* spp	300-355	**1.193**	**-0.091**
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Subbotina* spp	250-300	**1.360**	**-0.261**
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Subbotina* spp	212-250	**1.328**	**-0.149**
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Subbotina* spp	180-212	**1.590**	**-0.088**
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	300-355	**3.330**	**-0.682**
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	250-300	**3.195**	**-0.512**
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	212-250	**2.632**	**-0.682**
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	180-212	**2.482**	**-0.706**
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	300-355	**2.580**	**-0.706**
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	250-300	**2.687**	**-0.780**
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	212-250	**2.960**	**-0.504**
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	180-212	**2.865**	**-0.329**
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	150-180	**2.475**	**-0.537**
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	300-355	**2.427**	**-0.658**
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	250-300	**2.405**	**-0.723**
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	212-250	**1.759**	**-0.811**
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	180-212	**1.442**	**-1.141**
1051B-13H-5, 63-66 cm	111.43	40.87	*Subbotina* spp	250-300	**1.186**	**-0.050**
1051B-13H-5, 63-66 cm	111.43	40.87	*Subbotina* spp	212-250	**1.718**	**-0.295**

*CK95 = Age scale of Cande and Kent (1995).

†A broad species concept was adopted for *A. topilensis* (see Fig. DR4).

TABLE DR2. PLANKTIC FORAMINIFERAL SIZE FRACTION-δ13C AND δ18O DATA FROM ODP SITE 748

Sample	Depth (mbsf)	CK95* Age (Ma)	Taxon	Sieve size fraction (microns)	$\delta^{13}C$ VPDB	Average $\delta^{13}C$ VPDB	$\delta^{18}O$ VPDB	Average $\delta^{18}O$ VPDB
748B-18H-7, 23-25 cm	161.33	39.35	*Acarinina primitiva*	300-355	**3.01**		**-0.12**	
748B-18H-7, 23-25 cm	161.33	39.35	*Acarinina primitiva*	250-300	**3.19**		**-0.02**	
748B-18H-7, 23-25 cm	161.33	39.35	*Acarinina primitiva*	212-250	**2.84**		**0.01**	
748B-18H-7, 23-25 cm	161.33	39.35	*Acarinina primitiva*	180-212	**2.55**		**0.00**	
748B-18H-7, 23-25 cm	161.33	39.35	*Acarinina primitiva*	150-180	**2.39**		**0.07**	
748B-18H-7, 23-25 cm	161.33	39.35	*Globigerinatheka index*	>425	**3.18**		**0.16**	
748B-18H-7, 23-25 cm	161.33	39.35	*Globigerinatheka index*	355-425	**2.98**		**0.44**	
748B-18H-7, 23-25 cm	161.33	39.35	*Globigerinatheka index*	300-355	**2.91**		**0.42**	
748B-18H-7, 23-25 cm	161.33	39.35	*Globigerinatheka index*	250-300	**2.77**		**0.40**	
748B-18H-7, 23-25 cm	161.33	39.35	*Globigerinatheka index*	212-250	**2.66**		**0.22**	
748B-18H-7, 23-25 cm	161.33	39.35	*Globigerinatheka index*	180-212	**2.55**		**0.28**	
748B-18H-7, 23-25 cm	161.33	39.35	*Globigerinatheka index*	150-180	**2.33**		**0.22**	
748B-18H-7, 23-25 cm	161.33	39.35	*Subbotina spp.*	355-425	**1.88**		**0.77**	
748B-18H-7, 23-25 cm	161.33	39.35	*Subbotina spp.*	300-355	**1.87**		**0.75**	
748B-18H-7, 23-25 cm	161.33	39.35	*Subbotina spp.*	250-300	**1.88**		**0.79**	
748B-18H-7, 23-25 cm	161.33	39.35	*Subbotina spp.*	212-250	**1.82**		**0.81**	
748B-18H-7, 23-25 cm	161.33	39.35	*Subbotina spp.*	180-212	**1.81**		**0.66**	
748B-18H-7, 23-25 cm	161.33	39.35	*Subbotina spp.*	150-180	**1.74**		**0.54**	
748B-18H-7, 32-34 cm	161.42	39.36	*Acarinina primitiva*	250-300	**2.79**		**0.07**	
748B-18H-7, 32-34 cm	161.42	39.36	*Acarinina primitiva*	250-300	**2.86**	2.91	**0.10**	0.04
748B-18H-7, 32-34 cm	161.42	39.36	*Acarinina primitiva*	250-300	**3.07**		**-0.05**	
748B-18H-7, 32-34 cm	161.42	39.36	*Acarinina primitiva*	212-250	**2.81**		**-0.06**	
748B-18H-7, 32-34 cm	161.42	39.36	*Acarinina primitiva*	212-250	**2.97**	2.83	**-0.19**	-0.15
748B-18H-7, 32-34 cm	161.42	39.36	*Acarinina primitiva*	212-250	**2.88**		**-0.24**	
748B-18H-7, 32-34 cm	161.42	39.36	*Acarinina primitiva*	212-250	**2.66**		**-0.10**	
748B-18H-7, 32-34 cm	161.42	39.36	*Acarinina primitiva*	180-212	**2.47**		**0.19**	
748B-18H-7, 32-34 cm	161.42	39.36	*Acarinina primitiva*	180-212	**2.46**		**0.07**	
748B-18H-7, 32-34 cm	161.42	39.36	*Acarinina primitiva*	180-212	**2.52**	2.55	**-0.14**	0.00
748B-18H-7, 32-34 cm	161.42	39.36	*Acarinina primitiva*	180-212	**2.65**		**-0.01**	
748B-18H-7, 32-34 cm	161.42	39.36	*Acarinina primitiva*	180-212	**2.63**		**-0.11**	
748B-18H-7, 32-34 cm	161.42	39.36	*Acarinina primitiva*	150-180	**2.21**		**-0.03**	
748B-18H-7, 32-34 cm	161.42	39.36	*Acarinina primitiva*	150-180	**2.33**	2.37	**-0.07**	-0.06
748B-18H-7, 32-34 cm	161.42	39.36	*Acarinina primitiva*	150-180	**2.58**		**-0.08**	
748B-18H-7, 32-34 cm	161.42	39.36	*Globigerinatheka index*	355-425	**2.74**		**0.38**	
748B-18H-7, 32-34 cm	161.42	39.36	*Globigerinatheka index*	355-425	**2.97**	2.85	**0.25**	0.31
748B-18H-7, 32-34 cm	161.42	39.36	*Globigerinatheka index*	355-425	**2.85**		**0.30**	
748B-18H-7, 32-34 cm	161.42	39.36	*Globigerinatheka index*	300-355	**2.73**		**0.31**	
748B-18H-7, 32-34 cm	161.42	39.36	*Globigerinatheka index*	300-355	**2.77**	2.79	**0.39**	0.33
748B-18H-7, 32-34 cm	161.42	39.36	*Globigerinatheka index*	300-355	**2.94**		**0.29**	
748B-18H-7, 32-34 cm	161.42	39.36	*Globigerinatheka index*	300-355	**2.70**		**0.34**	
748B-18H-7, 32-34 cm	161.42	39.36	*Globigerinatheka index*	250-300	**2.73**		**0.36**	
748B-18H-7, 32-34 cm	161.42	39.36	*Globigerinatheka index*	250-300	**2.73**	2.69	**0.19**	0.30
748B-18H-7, 32-34 cm	161.42	39.36	*Globigerinatheka index*	250-300	**2.61**		**0.35**	
748B-18H-7, 32-34 cm	161.42	39.36	*Globigerinatheka index*	212-250	**2.34**		**0.40**	
748B-18H-7, 32-34 cm	161.42	39.36	*Globigerinatheka index*	212-250	**2.54**	2.50	**0.23**	0.27
748B-18H-7, 32-34 cm	161.42	39.36	*Globigerinatheka index*	212-250	**2.63**		**0.20**	
748B-18H-7, 32-34 cm	161.42	39.36	*Globigerinatheka index*	180-212	**2.42**	2.44	**0.17**	0.11
748B-18H-7, 32-34 cm	161.42	39.36	*Globigerinatheka index*	180-212	**2.47**		**0.12**	
748B-18H-7, 32-34 cm	161.42	39.36	*Globigerinatheka index*	180-212	**2.44**		**0.04**	
748B-18H-7, 32-34 cm	161.42	39.36	*Globigerinatheka index*	150-180	**2.08**		**0.30**	
748B-18H-7, 32-34 cm	161.42	39.36	*Globigerinatheka index*	150-180	**2.25**	2.24	**0.13**	0.15
748B-18H-7, 32-34 cm	161.42	39.36	*Globigerinatheka index*	150-180	**2.41**		**0.01**	
748B-18H-7, 32-34 cm	161.42	39.36	*Subbotina spp.*	250-300	**1.67**		**0.63**	
748B-18H-7, 32-34 cm	161.42	39.36	*Subbotina spp.*	250-300	**1.69**	1.70	**0.69**	0.67
748B-18H-7, 32-34 cm	161.42	39.36	*Subbotina spp.*	250-300	**1.75**		**0.67**	
748B-18H-7, 32-34 cm	161.42	39.36	*Subbotina spp.*	212-250	**1.69**		**0.65**	
748B-18H-7, 32-34 cm	161.42	39.36	*Subbotina spp.*	212-250	**1.69**	1.69	**0.67**	0.66
748B-18H-7, 32-34 cm	161.42	39.36	*Subbotina spp.*	212-250	**1.70**		**0.65**	
748B-18H-7, 32-34 cm	161.42	39.36	*Subbotina spp.*	180-212	**1.47**	1.59	**0.64**	0.58

748B-18H-7, 32-34 cm	161.42	39.36	*Subbotina spp.*	180-212	**1.67**		**0.54**	
748B-18H-7, 32-34 cm	161.42	39.36	*Subbotina spp.*	180-212	**1.69**		**0.50**	
748B-18H-7, 32-34 cm	161.42	39.36	*Subbotina spp.*	180-212	**1.53**		**0.65**	
748B-18H-7, 32-34 cm	161.42	39.36	*Subbotina spp.*	150-180	**1.54**	1.57	**0.39**	0.42
748B-18H-7, 32-34 cm	161.42	39.36	*Subbotina spp.*	150-180	**1.59**		**0.46**	
748B-19H-2, 127-129 cm	164.37	40.04	*Acarinina primitiva*	300-355	**2.10**		**-0.26**	
748B-19H-2, 127-129 cm	164.37	40.04	*Acarinina primitiva*	250-300	**2.25**		**-0.38**	
748B-19H-2, 127-129 cm	164.37	40.04	*Acarinina primitiva*	212-250	**1.95**		**-0.41**	
748B-19H-2, 127-129 cm	164.37	40.04	*Acarinina primitiva*	180-212	**1.94**		**-0.52**	
748B-19H-2, 127-129 cm	164.37	40.04	*Acarinina primitiva*	150-180	**1.86**		**-0.65**	
748B-19H-2, 127-129 cm	164.37	40.04	*Globigerinatheka index*	355-425	**1.98**		**-0.27**	
748B-19H-2, 127-129 cm	164.37	40.04	*Globigerinatheka index*	355-400	**1.99**		**-0.38**	
748B-19H-2, 127-129 cm	164.37	40.04	*Globigerinatheka index*	300-355	**1.94**	2.06	**-0.38**	-0.35
748B-19H-2, 127-129 cm	164.37	40.04	*Globigerinatheka index*	300-355	**2.17**		**-0.32**	
748B-19H-2, 127-129 cm	164.37	40.04	*Globigerinatheka index*	250-300	**1.78**		**-0.32**	
748B-19H-2, 127-129 cm	164.37	40.04	*Globigerinatheka index*	212-250	**1.92**		**-0.34**	
748B-19H-2, 127-129 cm	164.37	40.04	*Globigerinatheka index*	180-212	**1.85**		**-0.23**	
748B-19H-2, 127-129 cm	164.37	40.04	*Globigerinatheka index*	150-180	**1.40**		**-0.43**	
748B-19H-2, 127-129 cm	164.37	40.04	*Subbotina spp.*	300-355	**1.00**		**-0.21**	
748B-19H-2, 127-129 cm	164.37	40.04	*Subbotina spp.*	250-300	**1.10**		**-0.32**	
748B-19H-2, 127-129 cm	164.37	40.04	*Subbotina spp.*	212-250	**1.28**		**-0.16**	
748B-19H-2, 127-129 cm	164.37	40.04	*Subbotina spp.*	180-212	**1.20**		**-0.18**	
748B-19H-2, 127-129 cm	164.37	40.04	*Subbotina spp.*	150-180	**1.25**		**-0.24**	
748B-19H-3, 31-33 cm	164.91	40.08	*Acarinina primitiva*	300-355	**2.07**		**-0.40**	
748B-19H-3, 31-33 cm	164.91	40.08	*Acarinina primitiva*	250-300	**1.92**		**-0.42**	
748B-19H-3, 31-33 cm	164.91	40.08	*Acarinina primitiva*	212-250	**1.81**		**-0.59**	
748B-19H-3, 31-33 cm	164.91	40.08	*Acarinina primitiva*	180-212	**1.90**		**-0.47**	
748B-19H-3, 31-33 cm	164.91	40.08	*Acarinina primitiva*	150-180	**1.80**		**-0.38**	
748B-19H-3, 31-33 cm	164.91	40.08	*Globigerinatheka index*	>400	**2.24**		**-0.33**	
748B-19H-3, 31-33 cm	164.91	40.08	*Globigerinatheka index*	355-400	**2.02**		**-0.40**	
748B-19H-3, 31-33 cm	164.91	40.08	*Globigerinatheka index*	300-355	**1.83**		**-0.36**	
748B-19H-3, 31-33 cm	164.91	40.08	*Globigerinatheka index*	250-300	**1.79**		**-0.35**	
748B-19H-3, 31-33 cm	164.91	40.08	*Globigerinatheka index*	212-250	**1.76**		**-0.30**	
748B-19H-3, 31-33 cm	164.91	40.08	*Globigerinatheka index*	180-212	**1.87**		**-0.40**	
748B-19H-3, 31-33 cm	164.91	40.08	*Globigerinatheka index*	150-180	**1.76**		**-0.19**	
748B-19H-3, 31-33 cm	164.91	40.08	*Globigerinatheka index*	125-150	**1.49**		**-0.20**	
748B-19H-3, 31-33 cm	164.91	40.08	*Subbotina spp.*	300-355	**1.12**		**-0.14**	
748B-19H-3, 31-33 cm	164.91	40.08	*Subbotina spp.*	250-300	**1.22**		**-0.03**	
748B-19H-3, 31-33 cm	164.91	40.08	*Subbotina spp.*	212-250	**1.18**		**0.12**	
748B-19H-3, 31-33 cm	164.91	40.08	*Subbotina spp.*	180-212	**1.31**		**0.00**	
748B-19H-3, 31-33 cm	164.91	40.08	*Subbotina spp.*	150-180	**1.27**		**-0.13**	
748B-19H-3, 103-105 cm	165.63	40.13	*Acarinina primitiva*	300-355	**2.11**		**-0.14**	
748B-19H-3, 103-105 cm	165.63	40.13	*Acarinina primitiva*	250-300	**1.86**		**-0.15**	
748B-19H-3, 103-105 cm	165.63	40.13	*Acarinina primitiva*	212-250	**1.93**		**-0.18**	
748B-19H-3, 103-105 cm	165.63	40.13	*Acarinina primitiva*	180-212	**2.10**		**-0.34**	
748B-19H-3, 103-105 cm	165.63	40.13	*Acarinina primitiva*	150-180	**2.21**		**-0.63**	
748B-19H-3, 103-105 cm	165.63	40.13	*Acarinina primitiva*	125-150	**2.08**		**-0.50**	
748B-19H-4, 103-105 cm	167.13	40.24	*Acarinina primitiva*	300-355	**2.27**		**0.24**	
748B-19H-4, 103-105 cm	167.13	40.24	*Acarinina primitiva*	250-300	**1.89**		**0.04**	
748B-19H-4, 103-105 cm	167.13	40.24	*Acarinina primitiva*	180-212	**1.78**		**0.10**	
748B-19H-4, 103-105 cm	167.13	40.24	*Acarinina primitiva*	150-180	**1.84**		**0.23**	
748B-19H-4, 103-105 cm	167.13	40.24	*Acarinina primitiva*	125-150	**1.99**		**-0.16**	
748B-19H-5, 71-73 cm	168.31	40.30	*Acarinina primitiva*	300-355	**2.04**		**0.12**	
748B-19H-5, 71-73 cm	168.31	40.30	*Acarinina primitiva*	250-300	**1.94**		**0.11**	
748B-19H-5, 71-73 cm	168.31	40.30	*Acarinina primitiva*	212-250	**1.94**		**0.07**	
748B-19H-5, 71-73 cm	168.31	40.30	*Acarinina primitiva*	180-212	**1.90**		**0.00**	
748B-19H-5, 71-73 cm	168.31	40.30	*Acarinina primitiva*	150-180	**1.75**		**0.14**	
748B-19H-6, 55-57 cm	169.65	40.38	*Acarinina primitiva*	300-355	**2.06**		**0.03**	
748B-19H-6, 55-57 cm	169.65	40.38	*Acarinina primitiva*	250-300	**2.03**		**0.11**	
748B-19H-6, 55-57 cm	169.65	40.38	*Acarinina primitiva*	212-250	**1.79**		**0.08**	

748B-19H-6, 55-57 cm	169.65	40.38	*Acarinina primitiva*	180-212	**1.95**		**-0.29**	
748B-19H-6, 55-57 cm	169.65	40.38	*Acarinina primitiva*	150-180	**1.62**		**0.09**	
748B-19H-6, 55-57 cm	169.65	40.38	*Acarinina primitiva*	125-150	**1.72**		**0.19**	
748B-20H-1, 16-18 cm	171.26	41.41	*Acarinina primitiva*	300-355	**1.93**		**0.42**	
748B-20H-1, 16-18 cm	171.26	41.41	*Acarinina primitiva*	250-300	**1.85**		**0.22**	
748B-20H-1, 16-18 cm	171.26	41.41	*Acarinina primitiva*	212-250	**1.63**		**0.25**	
748B-20H-1, 16-18 cm	171.26	41.41	*Acarinina primitiva*	180-212	**1.46**		**0.29**	
748B-20H-1, 16-18 cm	171.26	41.41	*Acarinina primitiva*	150-180	**1.37**		**-0.14**	
748B-20H-1, 16-18 cm	171.26	41.41	*Globigerinatheka index*	355-400	**2.52**		**0.12**	
748B-20H-1, 16-18 cm	171.26	41.41	*Globigerinatheka index*	300-355	**2.46**		**-0.06**	
748B-20H-1, 16-18 cm	171.26	41.41	*Globigerinatheka index*	250-300	**2.23**		**0.05**	
748B-20H-1, 16-18 cm	171.26	41.41	*Globigerinatheka index*	212-250	**1.90**		**0.15**	
748B-20H-1, 16-18 cm	171.26	41.41	*Globigerinatheka index*	180-212	**1.80**		**0.16**	
748B-20H-1, 16-18 cm	171.26	41.41	*Globigerinatheka index*	150-180	**1.38**		**0.23**	
748B-20H-1, 16-18 cm	171.26	41.41	*Subbotina spp.*	300-355	**1.15**		**0.53**	
748B-20H-1, 16-18 cm	171.26	41.41	*Subbotina spp.*	250-300	**1.25**		**0.40**	
748B-20H-1, 16-18 cm	171.26	41.41	*Subbotina spp.*	212-250	**1.16**		**0.39**	
748B-20H-1, 16-18 cm	171.26	41.41	*Subbotina spp.*	180-212	**1.20**		**0.50**	
748B-20H-1, 16-18 cm	171.26	41.41	*Subbotina spp.*	150-180	**0.95**		**0.39**	
748B-20H-3, 76-78 cm	174.86	41.79	*Acarinina primitiva*	300-355	**1.57**		**-0.32**	
748B-20H-3, 76-78 cm	174.86	41.79	*Acarinina primitiva*	250-300	**1.25**		**-0.32**	
748B-20H-3, 76-78 cm	174.86	41.79	*Acarinina primitiva*	212-250	**0.92**	1.01	**-0.27**	-0.24
748B-20H-3, 76-78 cm	174.86	41.79	*Acarinina primitiva*	212-250	**1.11**		**-0.21**	
748B-20H-3, 76-78 cm	174.86	41.79	*Acarinina primitiva*	180-212	**0.85**	0.89	**-0.26**	-0.30
748B-20H-3, 76-78 cm	174.86	41.79	*Acarinina primitiva*	180-212	**0.92**		**-0.33**	
748B-20H-3, 76-78 cm	174.86	41.79	*Acarinina primitiva*	150-180	**0.79**		**-0.44**	
748B-20H-3, 76-78 cm	174.86	41.79	*Globigerinatheka index*	355-400	**1.60**		**-0.38**	
748B-20H-3, 76-78 cm	174.86	41.79	*Globigerinatheka index*	300-355	**1.39**		**-0.36**	
748B-20H-3, 76-78 cm	174.86	41.79	*Globigerinatheka index*	250-300	**1.37**		**-0.35**	
748B-20H-3, 76-78 cm	174.86	41.79	*Globigerinatheka index*	212-250	**1.17**		**-0.28**	
748B-20H-3, 76-78 cm	174.86	41.79	*Globigerinatheka index*	180-212	**1.14**		**-0.31**	
748B-20H-3, 76-78 cm	174.86	41.79	*Globigerinatheka index*	150-180	**0.81**		**-0.31**	
748B-20H-3, 76-78 cm	174.86	41.79	*Subbotina spp.*	300-355	**0.33**		**-0.01**	
748B-20H-3, 76-78 cm	174.86	41.79	*Subbotina spp.*	250-300	**0.56**		**-0.03**	
748B-20H-3, 76-78 cm	174.86	41.79	*Subbotina spp.*	212-250	**0.50**		**-0.08**	
748B-20H-3, 76-78 cm	174.86	41.79	*Subbotina spp.*	180-212	**0.54**		**-0.05**	
748B-20H-3, 76-78 cm	174.86	41.79	*Subbotina spp.*	150-180	**0.68**		**0.02**	

*CK95 = Age scale of Cande and Kent (1995).

TABLE DR3. CHANGE IN THE GRADIENT OF CARBON ISOTOPES WITH SIZE (δ^{13}C/100 MICRONS) OF PLANKTIC FORAMINIFERA

Sample	**Depth (mbsf)**	**CK95* Age (Ma)**	**CK95 Age (Ma) from Bohaty *et al*., 2009**	***Acarinina* spp† ($\Delta\delta^{13}$C/100 microns)**	***Morozovelloides crassatus* ($\Delta\delta^{13}$C/100 microns)**	***Globigerinatheka* spp§ ($\Delta\delta^{13}$C/100 microns)**	***Subbotina* spp ($\Delta\delta^{13}$C/100 microns)**	**Interval**
1051A-8H-6, 5-7 cm	69.14	39.90	-	0.68	0.63	0.83	0.00	Post-MECO
1051B-9H-5, 5-7 cm	77.35	40.05	-	0.14	0.50	0.34	0.20	Peak MECO
1051B-9H-6, 75-77 cm	79.47	40.16	-	0.95	0.75	0.49	0.01	Initial' MECO
1051B-11H-4, 45-47 cm	92.25	40.40	-	0.55	0.67	0.66	0.23	Initial' MECO
1051A-12H-3, 131.5-133 cm	105.1	40.78	-	0.62	0.40	1.06	0.00	Initial' MECO
1051B-13H-5, 63-66 cm	111.4	40.87	-	0.70	0.00	0.80	-	Pre-MECO
748B-18H-7, 23-25 cm	161.33	39.40	39.35	0.44	-	0.27	0.03	Post-MECO
748B-18H-7, 32-34 cm	161.42	39.41	39.36	0.51	-	0.29	0.15	Post-MECO
748B-19H-2, 127-129 cm	164.37	40.09	40.04	0.19	-	0.19	-0.15	Peak MECO
748B-19H-3, 31-33 cm	164.91	40.13	40.08	0.14	-	0.18	-0.14	Peak MECO
748B-19H-3, 103-105 cm	165.63	40.18	40.13	0.07	-	-	-	Peak MECO
748B-19H-4, 103-105 cm	167.13	40.29	40.24	0.15	-	-	-	Initial' MECO?
748B-19H-5, 71-73 cm	168.31	40.35	40.30	0.15	-	-	-	Initial' MECO?
748B-19H-6, 55-57 cm	169.65	40.43	40.38	0.21	-	-	-	Initial' MECO?
748B-20H-1, 16-18 cm	171.26	41.46	41.41	0.37	-	0.52	-0.03	Pre-MECO
748B-20H-3, 76-78 cm	174.86	41.84	41.79	0.47	-	0.32	-0.16	Pre-MECO

Note: All δ^{13}C/100 micron values are calculated independently for each taxon in every sample using linear regression and multiplying the resulting gradient by 100.

*CK95 = Age scale of Cande and Kent (1995).

†*Acarinina topilensis* and *Acarinina primitiva* analysed at ODP Sites 1051 and 748, respectively.

§*Globigerinatheka index* analysed at ODP Site 748.

TABLE DR4. CHANGE IN THE TEST SIZE-$\delta^{13}C$ GRADIENT ($\delta^{13}C$/100 MICRONS) OF MODERN AND PALEOGENE PLANKTIC FORAMINIFERA

Sample	**Species**	**Age (Ma)**	**$\Delta\delta^{13}C$/100 microns**	***Data source***
384, 11H-1, 128-136 cm	*Morozovella angulata*	Paleocene	0.55	Norris, 1996
384, 10H-CC	*Morozovella conicotruncata*	Paleocene	0.54	Norris, 1996
384, 6H-1, 30-32 cm	*Morozovella velascoensis*	Paleocene	0.74	Norris, 1996
384, 3H-4, 60-62 cm	*Morozovella acutaspira*	Paleocene	0.54	Norris, 1996
384, 6H-1, 30-32 cm	*Acarinina mckanni*	Paleocene	0.88	Norris, 1996
758A, 28-4, 24-26 cm	*Morozovella subbotinae*	Paleocene	0.46	D'Hondt et al., 1994
758A, 28-4, 24-26 cm	*Morozovella velascoensis*	Paleocene	0.35	D'Hondt et al., 1994
758A, 28-4, 24-26 cm	*Acarinina nitida*	Paleocene	0.62	D'Hondt et al., 1994
BOFS 31K	*Globigerinoides ruber* (white)	Modern	0.31	Elderfield et al., 2002
BOFS 31K	*Globigerinoides ruber* (pink)	Modern	-0.13	Elderfield et al., 2002
BOFS 31K	*Globigerinoides sacculifer*	Modern	0.67	Elderfield et al., 2002
BOFS 31K	*Orbulina universa*	Modern	0.54	Elderfield et al., 2002
61BC, 0-1 cm	*Globigerinoides ruber* (pink)	Modern	0.48	Bornemann and Norris, 2007
61BC, 0-1 cm	*Globigerinoides sacculifer*	Modern	0.41	Bornemann and Norris, 2007
KNR110, 1-3 cm	*Globigerinoides sacculifer*	Modern	0.42	Bornemann and Norris, 2007

Note: All $\delta^{13}C$/100 micron values are calculated independently for each taxon in every sample using linear regression and multiplying the resulting gradient by 100. For consistency and to avoid kinetic effects on $\delta^{13}C$ values at small test sizes we only use sieve size factions from >180 microns. Based on test size-$\delta^{13}C$ gradients alone, the Paleogene muricates and globigerinethekids were acquiring and using symbionts in a similar manner and as effectively as modern cancellate spinose forms. However, we note that as highlighted in this study, test size-d13C gradients are likely to vary spatially and through time.

TABLE DR5. MAXIMUM TEST DIAMETER OF PLANKTIC FORAMINIFERA AT ODP SITE 1051

Sample	**Depth (mbsf)**	**CK95* Age (Ma)**	**Taxon†**	**Maximum test diameter (microns)**
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	580
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	537
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	512
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	509
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	506
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	506
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	504
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	486
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	481
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	478
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	468
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	465
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	465
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	459
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	458
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	449
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	431
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	426
1051A-8H-6, 5-7 cm	69.14	39.90	*Acarinina topilensis*	402
1051A-8H-6, 5-7 cm	69.14	39.90	*Morozovelloides crassatus*	498
1051A-8H-6, 5-7 cm	69.14	39.90	*Morozovelloides crassatus*	489
1051A-8H-6, 5-7 cm	69.14	39.90	*Morozovelloides crassatus*	468
1051A-8H-6, 5-7 cm	69.14	39.90	*Morozovelloides crassatus*	444
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	411
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	403
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	403
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	402
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	401
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	397
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	396
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	395
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	395
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	393
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	393
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	391
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	389
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	388
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	386
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	386
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	384
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	383
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	372
1051A-8H-6, 5-7 cm	69.14	39.90	*Globigerinatheka* spp	359
1051B-9H-5, 5-7 cm	77.35	40.05	*Acarinina praetopilensis-topilensis*	411
1051B-9H-5, 5-7 cm	77.35	40.05	*Acarinina praetopilensis-topilensis*	374

1051B-9H-5, 5-7 cm	77.35	40.05	*Acarinina praetopilensis-topilensis*	306
1051B-9H-5, 5-7 cm	77.35	40.05	*Acarinina praetopilensis-topilensis*	282
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	561
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	553
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	545
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	521
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	511
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	505
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	504
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	504
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	504
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	501
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	496
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	489
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	480
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	479
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	479
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	477
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	476
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	460
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	458
1051B-9H-5, 5-7 cm	77.35	40.05	*Morozovelloides crassatus*	433
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	667
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	603
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	574
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	569
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	563
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	542
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	541
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	541
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	539
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	535
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	532
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	530
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	509
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	476
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	453
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	448
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	437
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	426
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	426
1051B-9H-5, 5-7 cm	77.35	40.05	*Globigerinatheka* spp	418
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	541
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	503
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	497
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	489
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	473
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	472
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	463
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	462

1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	459
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	451
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	450
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	449
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	448
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	447
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	444
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	443
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	442
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	441
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	441
1051B-9H-6, 75-77 cm	79.47	40.16	*Acarinina topilensis*	440
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	544
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	503
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	498
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	489
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	475
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	472
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	463
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	460
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	459
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	452
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	451
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	450
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	447
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	447
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	444
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	443
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	442
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	441
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	440
1051B-9H-6, 75-77 cm	79.47	40.16	*Morozovelloides crassatus*	439
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	646
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	639
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	637
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	637
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	628
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	620
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	619
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	614
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	611
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	604
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	604
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	588
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	587
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	562
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	544
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	540
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	517
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	479
1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	470

1051B-9H-6, 75-77 cm	79.47	40.16	*Globigerinatheka* spp	455
1051B-11H-4, 45-47 cm	92.25	40.40	*Acarinina topilensis*	588
1051B-11H-4, 45-47 cm	92.25	40.40	*Acarinina topilensis*	542
1051B-11H-4, 45-47 cm	92.25	40.40	*Acarinina topilensis*	538
1051B-11H-4, 45-47 cm	92.25	40.40	*Acarinina topilensis*	528
1051B-11H-4, 45-47 cm	92.25	40.40	*Acarinina topilensis*	506
1051B-11H-4, 45-47 cm	92.25	40.40	*Acarinina topilensis*	506
1051B-11H-4, 45-47 cm	92.25	40.40	*Acarinina topilensis*	495
1051B-11H-4, 45-47 cm	92.25	40.40	*Acarinina topilensis*	494
1051B-11H-4, 45-47 cm	92.25	40.40	*Acarinina topilensis*	480
1051B-11H-4, 45-47 cm	92.25	40.40	*Acarinina topilensis*	471
1051B-11H-4, 45-47 cm	92.25	40.40	*Acarinina topilensis*	461
1051B-11H-4, 45-47 cm	92.25	40.40	*Acarinina topilensis*	460
1051B-11H-4, 45-47 cm	92.25	40.40	*Acarinina topilensis*	456
1051B-11H-4, 45-47 cm	92.25	40.40	*Acarinina topilensis*	438
1051B-11H-4, 45-47 cm	92.25	40.40	*Acarinina topilensis*	431
1051B-11H-4, 45-47 cm	92.25	40.40	*Morozovelloides crassatus*	529
1051B-11H-4, 45-47 cm	92.25	40.40	*Morozovelloides crassatus*	526
1051B-11H-4, 45-47 cm	92.25	40.40	*Morozovelloides crassatus*	519
1051B-11H-4, 45-47 cm	92.25	40.40	*Morozovelloides crassatus*	519
1051B-11H-4, 45-47 cm	92.25	40.40	*Morozovelloides crassatus*	506
1051B-11H-4, 45-47 cm	92.25	40.40	*Morozovelloides crassatus*	503
1051B-11H-4, 45-47 cm	92.25	40.40	*Morozovelloides crassatus*	501
1051B-11H-4, 45-47 cm	92.25	40.40	*Morozovelloides crassatus*	494
1051B-11H-4, 45-47 cm	92.25	40.40	*Morozovelloides crassatus*	487
1051B-11H-4, 45-47 cm	92.25	40.40	*Morozovelloides crassatus*	478
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	495
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	412
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	411
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	406
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	404
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	403
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	396
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	395
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	393
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	391
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	389
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	388
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	388
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	384
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	384
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	384
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	378
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	378
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	378
1051B-11H-4, 45-47 cm	92.25	40.40	*Globigerinatheka* spp	377
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	617
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	614
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	596

1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	590
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	585
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	578
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	578
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	574
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	570
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	567
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	563
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	556
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	550
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	548
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	547
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	543
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	543
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	540
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	539
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Acarinina topilensis*	538
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	558
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	523
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	516
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	506
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	504
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	497
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	496
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	496
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	495
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	492
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	490
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	485
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	483
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	482
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	480
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	474
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	474
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	473
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	472
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Morozovelloides crassatus*	472
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	729
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	663
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	642
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	597
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	418
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	413
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	401
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	397
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	396
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	395
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	386
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	385
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	384
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	377

1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	376
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	376
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	370
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	368
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	367
1051A-12H-3, 131.5-133 cm	105.12	40.78	*Globigerinatheka* spp	363
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	571
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	538
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	534
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	513
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	507
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	505
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	501
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	499
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	497
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	494
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	477
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	476
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	475
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	464
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	462
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	461
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	459
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	457
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	453
1051B-13H-5, 63-66 cm	111.43	40.87	*Acarinina topilensis*	436
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	546
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	506
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	502
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	499
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	495
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	482
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	478
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	473
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	467
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	465
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	462
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	462
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	461
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	461
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	458
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	457
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	454
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	453
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	444
1051B-13H-5, 63-66 cm	111.43	40.87	*Morozovelloides crassatus*	443
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	389
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	389
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	389
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	386

1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	384
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	381
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	380
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	380
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	379
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	379
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	378
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	367
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	363
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	362
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	361
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	360
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	359
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	355
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	353
1051B-13H-5, 63-66 cm	111.43	40.87	*Globigerinatheka* spp	352

*CK95 = Age scale of Cande and Kent (1995).

†A broad species concept was adopted for *A. topilensis* (see Fig. DR4).

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