Abstract

Benthic foraminiferal assemblages were studied in 44 samples from lower and middle Eocene sediments in Integrated Ocean Drilling Program (IODP) Expedition 320 Holes U1331C, U1333A, and U1333B. The benthic foraminifers from Hole U1331C were sampled in lower Eocene calcareous nannofossil Zones NP12/NP13 and radiolarian Zones RP8/RP9, and thus fall within the early Eocene climatic optimum and those from Holes U1333A and U1333B fall in the upper lower Eocene and lower middle Eocene calcareous nannofossil Zones NP15–NP17 and radiolarian Zones RP13–RP16. The benthic foraminiferal assemblages from Hole U1331C are poorly preserved, so the paleoceanographic response of the benthic assemblage to warming could not be clearly observed. The diversity of benthic assemblages in the middle Eocene is positively correlated with the carbonate content of the samples. The species *Globocassidulina globosa*, which has been argued to be an opportunistic species, occurred in the high-carbonate intervals. Diversities decreased coeval with an increase in abundance of radiolarians, occurring between Sections 320-U1333A-16X-5 and 16X-6, at the time of deposition of the marked carbonate poor horizon in the middle Eocene.

Introduction

Development of Cenozoic benthic foraminiferal assemblages after the prominent extinction during the Paleocene/Eocene Thermal Maximum (PETM; ~56 Ma) has been correlated to periods of global cooling and associated changes in oceanic environments (Kennett and Stott, 1991; Thomas, 2007). Before development of Antarctic ice sheets during the major global cooling at the end of the Eocene, however, several smaller hyperthermals occurred following the PETM, culminating in the early Eocene climatic optimum (EECO, ~52 Ma). These smaller hyperthermals resemble the PETM in geochemical and biotic features (Lourens et al., 2005; Agnini et al., 2009; Zachos et al., 2010; Stap et al., 2010).

Deep-sea benthic foraminifers thus experienced severe climatic fluctuations during latest Paleocene to middle Eocene times. The cause of the benthic extinction during the PETM is still not fully understood, but one convincing explanation could be the change in adaptive strategy of the benthic foraminifers to changes of bentho-pelagic coupling as recognized in the modern ocean (Gooday,
2003; Thomas, 2007), possibly due to changes in temperature and thus metabolic rates, which could have led to the expansion of the trophic resource continuum (D’haenens et al., 2012), which also related to the global change in ocean ventilation, oxygenation, and productivity (Winguth et al., 2012). Changes in climatic-related oceanic productivity and export productivity thus could have strongly influenced benthic foraminiferal assemblages, and investigating the mode and tempo of the development of early to middle Eocene benthic assemblages may significantly add to our understanding of the mechanisms of paleoceanographic and biotic co-evolution.

Integrated Ocean Drilling Program (IODP) Expedition 320 and Ocean Drilling Program (ODP) Leg 199 (Pacific Equatorial Age Transect [PEAT]) provided unique paleoceanographic information that will be useful for the further development of an orbitally tuned geological timescale because the sites were well placed to obtain information along gradients in paleolatitude, paleodepth, and paleoproductivity. Eocene carbonate-rich sediments were recovered and used to recognize and define carbonate accumulation events (CAE) (Lyle et al., 2005; Pälike et al., 2009). These sites also allowed reconstruction of changes in the carbonate compensation depth (CCD) over time (Pälike et al., 2009), allowing us to test whether there were correlations between biotic evolution and the oceanic carbonate cycle (Griffith et al., 2010).

This report continues our description of lower Eocene benthic foraminifers from ODP Leg 199 Sites 1215, 1220, and 1221 (Nomura and Takata, 2005). The benthic assemblages at IODP Sites U1331 and U1333 at abyssal paleodepths are comparable to those at ODP Sites 1215, 1220, and 1221, also in the abyssal zone (~3000 m paleodepth). These results are very significant to adding to further information from the deeper ocean (Fig. F1).

Methods

Four samples from CaCO₃-rich sediments from Sections 320-U1331C-17H-3 and 17H-4, 31 samples from Sections 320-U1333A-16X-1 to 20X-2, and 9 samples from Sections 320-U1333B-19X-1 to 20X-3 were analyzed. All samples extended over 2 cm of core and were from the few levels in the lower Eocene and lower middle Eocene where carbonate-rich sediments were present (Pälike et al., 2009).

Samples were dried at 70°–80°C overnight and then weighed. Dried sediment samples were treated with 3% hydrogen peroxide solution overnight and washed through a 63 µm nylon mesh sieve. The residue was then dry-sieved over a 149 µm sieve, and foraminifers were picked from aliquots of the >149 µm size fraction. Because of low abundances of foraminifers in some sections, the numbers of foraminifers counted was less than 200 individuals in some samples. All picked foraminifers were arranged on an assemblage slide for identification of species. The diversity and equitability of the assemblages were estimated using the Shannon-Wiener index. The main source of foraminiferal systematics is Loeblich and Tappan (1988), which compiled well-known works of Plummer (1926), Cushman and Jarvis (1932), Cushman (1946, 1951), and Brotzen (1948). We examined the systematic works of Tjalsma and Lohmann (1983), van Morkhoven et al. (1986), and Jones (1994) for the cosmopolitan deep-sea foraminifers and Kaminski and Gradstein (2005) for the paleogene agglutinated foraminifers.

Results

Hole U1331C

A total of 29 benthic foraminiferal taxa were recognized (Table T1). Preservation of benthic foraminifers at Site U1331 is poor due to diagenesis caused by circulation of pore waters through the underlying basalt. Calcareous forms were poorly preserved, with recrystallized walls. The number of foraminifers per gram of sediment ranges from 1 to 7, very low numbers compared to normal deep-sea sediments. Foraminifers that do not use carbonate to agglutinate such as Ammobaculites truempyi, Oridorsalis umbonatus, Anomalinae spissiformis, and Quadratobulimina pyramidalis, appeared only in the uppermost sample studied. It is not clear whether these forms are present because of the shallow CCD or because of local influences. The East Pacific CCD in the early Eocene was located at a relatively shallow depth of 3000–3500 m. The early Eocene paleodepth of Site U1331 was near this CCD but was slightly above the CCD (Pälike et al., 2009).

The most common calcareous forms, Nuttallides truempyi, Oridorsalis umbonatus, Anomalinae spissiformis, and Quadratobulimina pyramidalis, appeared only in the uppermost sample studied. This assemblage is similar to the normal deep-sea assemblage in the early to early middle Eocene, although it has very low species richness.

Hole U1333A

A total of 79 foraminiferal taxa were recognized in this hole (Table T2). The preservation of benthic for-
aminifers was generally moderate, with recrystallization of the walls in the lower samples, but poor preservation and corroded walls as well as low abundance in the upper interval from Samples 320-U1333A-16X-1, 24–27 cm, through 16X-4, 75–77 cm. The absolute abundance (number of foraminifers per gram of sediment) fluctuates, being higher in the two higher intervals from Samples 320-U1333A-16X-6, 75–77 cm, to 17X-5, 75–77 cm, and 19X-3, 125–127 cm, to 20X-3, 25–27 cm. The former yields 12.9 individuals per gram, and the latter yields 31.8 individuals per gram. A distinct decrease in species number is recognized between Samples 320-U1333A-16X-5, 75–77 cm, and 16X-6, 75–77 cm, decreasing from 27 to 11 taxa. In general, the number of foraminifers per gram of sediment is negatively correlated with the abundance of radiolarians and positively correlated with the carbonate content, with highest numbers during the middle Eocene carbonate accumulation events (CAE 2–3). The species diversity changes from 3.0–4.0 to 0.7–3.0 and the species equitability changes from 0.5–0.6 to 0.7–0.9 between samples with low and high carbonate content. Although a distinct change in species diversity and equitability occurred, the main constituents of the assemblage did not change, suggesting that the decreased abundance is due to dilution with radiolarians rather than dissolution. Agglutinated foraminifers were common in abundance.

The most common species are Karreriella subglabra, Spiroplectammina spectabilis, Abyssamina quadrata, Abalamina dissonata, A. spissiformis, Cibicidoides eocaenatus, Cibicidoides grimscalei, Gyroidinoides girardanus, N. truempyi, O. umbonatus, Siphonodosaria aculeata, pleurostomellids, and species of Pullenia.

**Hole U1333B**

A total of 67 taxa were recognized in the nine samples studied from Hole U1333B (Table T3). The assemblage in Samples 320-U1333B-20X-1, 73–75 cm, to 20X-2, 73–75 cm, is similar to that recognized in Samples 320-U1333A-19X-4, 25–27 cm, to 20X-1, 25–27 cm, with abundant foraminifers per gram of sediment. In general, the preservation is moderate to poor, and specimens have recrystallized walls. The foraminiferal species are similar to those in Hole U1333A, including C. grimselfei, C. eocaenatus, A. dissonata, A. quadrata, A. spissiformis, G. girardanus, N. truempyi, O. umbonatus, and nodogenerinids. Most have large tests with thick walls. The assemblage shows a similar level of species diversity, 3.0–4.0, and similar levels of species equitability, 0.5–0.7.

**Early and middle Eocene benthic foraminiferal assemblages**

Because of the poor preservation of foraminifers in Hole U1331C and the fact that we found foraminifers in four samples only, we could not observe evidence of any foraminiferal response to the EECO. Carbonate-free agglutinated foraminifers such as Thalmanammina and Cyclammina occurred only in the lower Eocene, but they are not diagnostic of this climatic optimum (Kaminski and Gradstein, 2005). Rather, they indicate the presence of carbonate-corrosive deep water, as also suggested by the occurrence at other sites of Eocene radiolarian ooze and low-carbonate sediments (Shipboard Scientific Party, 2002). In the early Eocene, Hole U1331C was above the CCD (Pälike et al., 2009), but the common occurrence of the agglutinated taxa indicates that this site did not present a good habitat for calcifying foraminifers or these forms did live there but were not preserved, possibly due to circulation of hydrothermal fluids through the underlying basalts. The lowermost Eocene calcareous sediments directly above the basement basalt contain zeolitic clays formed by such hydrothermal circulation (Pälike et al., 2009). However, sediments further away from the basement basalt are less influenced by hydrothermal activity; thus, the calcareous assemblage could be preserved as seen in Sample 320-U1331C-17H-3, 78–80 cm, with N. truempyi, O. umbonatus, A. spissiformis, and A. quadrata. These species are also major constituents of assemblages occurring after the Paleocene/Eocene benthic extinction at Site 1220, near Hole U1331C (Nomura and Takata, 2005). However, the assemblage in Hole U1331C differs from that of Site 1220 in having lower species diversity. The most common species at Site 1220 include Bulimina bradburyi, Bulimina trihedra, Globocassidulina globosa, Pleurostomella paleocenica, Pullenia subcarinata, Quadrimorphina profunda, Tappanina selmensis, and small-sized Valvalabamina, but these are not as common in the assemblage in Hole U1331C. Except for the low-diversity Samples 320-U1333A-16X-1, 25–27 cm, to 16X-5, 75–77 cm, foraminifers in both holes at Site U1333 show almost the same assemblage, characterized by common cosmopolitan species such as N. truempyi, C. grimselfei, C. eocaenatus, and O. umbonatus. Their distribution in core sections shows a prominent foraminiferal occurrence at ~200 revised meters composite depth (rmcd) (Fig. F2), which may indicate correlation to either the CAE 2 (47.9–46.9 Ma) or CAE 1 (45.9–44.2 Ma) event. How-
ever, the age of the highest foraminiferal samples and correlation to CAE 2 or CAE 1 is uncertain, with nannofossil datums indicating the age of ~200.0–200.4 rmcld at ~45–47 Ma (Westehold et al., 2012), with both CAE 1 and CAE 2 occurring within this time interval. A distinct decrease in foraminiferal abundance between Sections 320-U1333A-16X-5 and 16X-6 (174.1–175.5 rmcld) occurring in Magneto-chron C18r is correlated with CAE 3, which occurred also in Magneto-chron C18r. CAE 3 is associated with shallowing of the CCD at the end of the event (Lyle et al., 2005).

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References


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Appendix
Faunal reference list

Agglutinated foraminifers
Ammobaculites sp.
Ammonovellinitina prima Suleymanov, 1959 (Pl. P1, fig. 9).
Bathysiphon sp.
Cyclammina elegans Cushman and Jarvis, 1928 (Pl. P1, fig. 5).
Gaudryina retusa Cushman, 1926 (Pl. P1, fig. 1).
Gaudryina sp.
Karreriella sp.

Karreriella subglabra (Cushman) (Pl. P1, fig. 3) = Gaudryina subglabra Gümbel, 1868.

Marssonella trochoides (d’Orbigny) (Pl. P1, fig. 2) = Gaudryina crassa Marsson var. trochoides Marsson, 1878.
Paratrochamminoides olszewskii (Grzybowski) (Pl. P1, figs. 6, 7) = Trohamminoides olszewski Gyrybowski, 1898.
Psammiphiphella cylindrica (Glaessner) (Pl. P1, fig. 4) = Rhabdammina cylindrica Glaessner, 1937.
Spiroplectammina spectabilis (Grzybowski) (Pl. P2, fig. 1) = Spiroplecta spectabilis Grzybowski, 1898.

Textularia plummerae Lalicker, 1935 (Pl. P9, fig. 1).

Textularia sp.

Thalmanammina conglobata (Brady) (Pl. P1, fig. 11) = Trohamminoides conglobata Brady, 1884.

Tritaxia globulifera (ten Dam and Sigal) (Pl. P1, figs. 12, 13) = Pseudoclavulina globulifera ten Dam and Sigal, 1950.

Tritaxia paleocenica Tjalsma and Lohmann, 1983.

Tritaxia pyramidata (Cushman) = Gaudryina laevigata Frane var. pyramidata Cushman, 1926.

Vulvalina spinosa Cushman, 1927 (Pl. P2, figs. 2–4).

Calcereous hyaline foraminifers
Abbyssinina quadrata Schnitker and Tjalsma, 1980 (Pl. P5, figs. 4, 5).
Abalammna dissonata (Cushman and Renz) (Pl. P8, figs. 6–8) = Pulvinulina atlantiasi Cushman var. dissonata Cushman and Renz, 1948.
Amplexoprodactyla carnalolintra Patterson, 1986 (Pl. P4, figs. 16, 17).

Anomalinoidea rubiginosus (Cushman) (Pl. P6, figs. 4, 5) = Anomalina rubiginosa Cushman, 1926.

Anomalinoidea spissiformis (Cushman and Stainforth) (Pl. P6, figs. 1–3) = Anomalina alazansensis Nuttall var. spissiformis Cushman and Stainforth, 1945.

Aragonina aragonensis (Nuttall) (Pl. P5, fig. 19) = Textularia aragonensis Nuttall, 1930.
Bandella greatvalleyensis (Trujillo) (Pl. P4, figs. 8, 9, 13) = Pleurostomella greatvalleyensis Trujillo, 1960.

Buliminina bradburyi Martin, 1943.
Buliminina impendens Parker and Bermudez, 1937 (Pl. P9, fig. 5).

Buliminina jarvisi Cushman and Parker, 1936 (Pl. P5, fig. 15).
Buliminella tuxpamensis Cole, 1928 (Pl. P5, figs. 8, 9).

Buliminella beaumontii Cushman and Renz, 1946 (Pl. P5, figs. 10, 11).

Cibicidoides bradyi (Trauth) (Pl. P7, fig. 6) = Truncatulina bradyi Trauth, 1918.

Cibicidoides eocaenus (Gümbl) (Pl. P7, figs. 4, 5) = Rotalia eocaena Gümbl, 1868.

Cibicidoides grimsdalei (Nuttall) (Pl. P7, figs. 1–3) = Cibicides grimsdalei Nuttall, 1930.

Cibicidoides spp.
Clynoptina inflata Tjalsma and Lohmann, 1983 (Pl. P9, fig. 9).
Clynoptina subplanispira Tjalsma and Lohmann, 1983 (Pl. P9, fig. 10).

Coryphostoma crenulata (Cushman) (Pl. P5, fig. 7) = Bolivina crenulata Cushman, 1936.

Dentalina annulata (Reuss) = Nodosaria annulata Reuss, 1844.

Dentalina guttatera d’Orbigny, 1846 (Pl. P3, fig. 12).

Dentalina reflexa Morrow, 1934 (Pl. P3, figs. 5, 6).

Dentalina spp.

Dentalina subsulata (Cushman) = Nodosaria subsulata Cushman, 1923.

Ellipsoglandulina ovata Gawor-Biedowa, 1992 (Pl. P4, fig. 18).

Ellipsoidella pleurostomellae Heron-Allen and Earlond, 1910 (Pl. P2, fig. 7; Pl. P4, Fig. 12).

Ellipsopopomorphina sp. (Pl. P2, fig. 14).

Ellipsopopomorphina spp.
Eouvigerina hispida Cushman, 1931 (Pl. P9, fig. 2).

Glandulonodosaria ambugia (Neugeboren) (Pl. P3, fig. 4) = Nodosaria ambugia Neugeboren, 1856.

Globocassidulina globosa (Hantken) (Pl. P5, figs. 17, 18) = Cassidulina globosa Hantken, 1875.

Globulina gibba (d’Orbigny) (Pl. P2, fig. 5) = Polymorpha gibba d’Orbigny, 1826.

Gyroidinoides beisseli (White) = Gyroidina beisseli White, 1928.
Gyroidinoides girardanus (Reuss) (Pl. P8, fig. 5) = Rotalina girardanus Reuss, 1851.

Gyroidinoides cf. globosus (Hagenow) (Pl. P8, fig. 4) = cf. Nonionia globosa Von Hagenow, 1842.

Gyroidinoides spp.

Hemiobulina sp.

Heronallenia lingulata (Burrows and Holland) (Pl. P5, fig. 20) = Discorbina lingulata Burrow and Holland, 1895.

Lenticulina insulsus (Cushman) (Pl. P6, fig. 10) = Robulus insulsus Cushman, 1947.

Lenticulina spp. (Pl. P6, fig. 11).

Linaresia semicribrata (Beckmann) = Anomalina pompilioides Galloway and Hemingway var. semicribrata Beckmann, 1954.

Marginulina glabra d’Orbigny, 1826 (Pl. P2, fig. 10).

Marginulina sp. (Pl. P2, fig. 9).

Marginulinopsis sp.

Nodosarella sp.

Nodosarella rotundata (D’Orbigny) (Pl. P2, fig. 6) = Lingulina rotundata d’Orbigny, 1846.

Nodosarella tuberosa (Gümbel) (Pl. P3, fig. 7; Pl. P4, fig. 15) = Lingulina tuberosa Gümbel, 1868.

Nodosaria annulata Reuss, 1844 (Pl. P3, fig. 11).

Nodosaria jarvisi (Cushman) (Pl. P3, fig. 3) = Ellipsonodosaria ? jarvisi Cushman, 1936.

Nodosaria naumannii Reuss (Pl. P3, fig. 1) = Nodosaria (Nodosaria) naumannii Reuss, 1875.

Nodosaria spp.

Nodosaria velascoensis Cushman (Pl. P3, fig. 2) = Nodosaria fontannesii Berthelin var. velascoensis Cushman, 1926.

Nonion havanense Cushman and Bermudez, 1937 (Pl. P5, fig. 16).

Nonion spp.


Obliquilingulina oblonga Zheng, 1979 (Pl. P2, fig. 15).

Oridorsalis plummerae (Cushman) (Pl. P2, fig. 11) = Eponides plummerae Cushman, 1948.

Oridorsalis umbonatus (Reuss) (Pl. P8, figs. 9–11) = Rotalina umbonata Reuss, 1851.

Orthomorphina havanensis (Cushman and Bermudez) (Pl. P4, fig. 10) = Nodosgenerina havanensis Cushman and Bermudez, 1937.

Orthomorphina sp.

Osangularia plummerae Brotzen, 1940 (Pl. P5, figs. 1–3).

Paralabamina elevata (Plummer) (Pl. P9, fig. 8) = Truncatulina elevata Plummer, 1927.

Pleurostomella clavata Cushman, 1926 (Pl. P2, fig. 8).

Pleurostomella subnodosa Reuss, 1860 (Pl. P4, fig. 14).

Pseudonodosaria appressa (Loeblich and Tappan) (Pl. P3, figs. 9, 10) = Rectoglandulina appressa Loeblich and Tappan, 1955.

Pseudonodosaria obesa (Loeblich and Tappan) (Pl. P3, fig. 8) = Rectoglandulina obesa Loeblich and Tappan, 1955.

Pullenia cf. eocenica Cushman and Siegfus, 1939.

Pullenia coryelli White, 1929 (Pl. P6, figs. 6, 7).

Pullenia cretacea Cushman, 1936 (Pl. P9, fig. 4).

Pullenia jarvisi Cushman, 1936 (Pl. P6, figs. 8, 9).

Pullenia sp.

Pyurilina sp.

Pyurilinoides acuminatus (d’Orbigny) (Pl. P2, fig. 13) = Pyurilina acuminata d’Orbigny, 1840.

Quadratobuliminella pyramidalis de Klasz, 1953 (Pl. P5, figs. 12–14).

Saracenaria midwayensis Kline, 1943 (Pl. P2, fig. 12).

Siphonodosaria aculeata (Cushman and Renz) (Pl. P4, figs. 2–5) = Ellipsonodosaria nuttalli var. aculeata Cushman and Renz, 1948.

Stilostomella gracillima (Cushman and Jarvis) (Pl. P4, fig. 7) = Ellipsonodosaria nuttalli var. gracillima Cushman and Jarvis, 1934.

Stilostomella hispidula (Cushman) (Pl. P4, fig. 6) = Ellipsonodosaria atlantias var. hispida Cushman, 1939.

Stilostomella jacksonensis (Cushman and Applin) (Pl. P4, fig. 1) = Nodosaria jacksonensis Cushman and Applin, 1926.

Strictocostella prolata (Cushman and Bermudez) (Pl. P4, fig. 11) = Ellipsonodosaria modesta var. prolata Cushman and Bermudez, 1937.

Tappanina selmensis (Cushman) (Pl. P9, fig. 6) = Bolivina selmensis Cushman, 1933.

Valvalabamina depressa (Alth) (Pl. P9, fig. 7) = Rotalina depressa Alth, 1850.

Valvulineria spp.

Virgulinopsis navarroana (Cushman) (Pl. P5, fig. 6) = Virgulina navarroana Cushman, 1933.

Unilocular forms
Figure F1. Site map for DSDP, ODP, and IODP in the equatorial central Pacific Ocean. F.Z. = fracture zone.
Figure F2. Benthic foraminiferal occurrences. Arrows indicate the marked stratigraphic levels of the foraminiferal assemblage.
**Table T1. Distribution of benthic foraminifers, Hole U1331C.**

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<th>Core, section, interval (cm)</th>
<th>Middepth (mbsf)</th>
<th>Sample weight (g)</th>
<th>Sample division number</th>
<th>Sample weight examined (g)</th>
<th>Foraminifer number/g sediment</th>
<th>Species diversity (H')</th>
<th>Equitability (E)</th>
<th>Agglutinated forms</th>
<th>Calcareous forms</th>
<th>Total number of specimens</th>
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* = adjusted revised CCSF-A.
Table T2. Distribution of benthic foraminifers, Hole U1333A. (Continued on next page.)

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### Table T3. Distribution of benthic foraminifers, Hole U1333B.

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