Global implications of lower to middle Eocene sequence boundaries on the New Jersey coastal plain: The icehouse cometh

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ABSTRACT

We document nine lower-middle Eocene sequences on the New Jersey coastal plain and compare them with global $\delta^{18}O$ and Haq et al. records. Early Eocene hiatuses do not match $\delta^{18}O$ changes, and it is unlikely that they are the result of glacioeustasy, consistent with an ice-free early Eocene. Early-middle Eocene (49–43 Ma) evidence for a link between sequences and $\delta^{18}O$ is equivocal, and the presence of large ice sheets is uncertain. Beginning in the late-middle Eocene (43–42 Ma), concomitant increases in planktonic and benthic $\delta^{18}O$ records coincide with the timing of hiatuses on the New Jersey coastal plain and a change from carbonate-dominated to siliciclastic-dominated sedimentation. These represent the development of the Antarctic ice cap and the beginning of the "icehouse" world. Of the 14 sequences predicted by Haq et al. for this interval, 9 are resolvable on the New Jersey margin, and the other 5 appear to be combined with others. We conclude that although ice-volume changes controlled sequences since at least 42 Ma, mechanisms for sea-level change prior to then are still not fully understood.

INTRODUCTION

Because of debates over mechanism, the Eocene provides a critical interval for evaluating causes of global sea-level (eustatic) change and the validity of sequence stratigraphy for global correlations. The only known mechanism for producing the large, rapid sea-level changes that have been reported for this interval is glacioeustasy (Donovan and Jones, 1979). Minimum benthic foraminiferal $\delta^{18}O$ values are associated with peak Cenozoic warmth in the early Eocene (Fig. 1), an interval believed to lack significant ice sheets (Miller et al., 1987). Global climate cooled in at least two steps in the early-middle and late-middle Eocene (Miller et al., 1987), although the role of ice sheets versus cooling associated with the increases is still debated (e.g., Barron et al., 1991). By the Oligocene, a large ice sheet existed at least intermittently in the Antarctic (Miller et al., 1991).

Although there is general agreement that there were no significant early Eocene ice sheets, Haq et al. (1987) predicted numerous early Eocene sequence boundaries and associated sea-level lowerings (Figs. 1 and 2). There are four solutions to this apparent paradox:

1. The early Eocene sequences summarized by Haq et al. (1987) were restricted to local basin(s) and do not reflect eustasy.
2. The sequences were controlled by low-amplitude sea-level changes (e.g., 10 m of lowering in 1 m.y. can be explained by numerous mechanisms; Donovan and Jones, 1979).
3. Mechanisms of sea-level change are not fully understood.
4. There were ice sheets throughout much of the Cretaceous to early Eocene. If so, then sea-level changes should be reflected in global $\delta^{18}O$ records.

Few studies of Eocene sections have attained direct ties to the Geomagnetic Polarity Time Scale (GPTS) and the high stratigraphic resolution (better than 0.5 m.y.) needed to evaluate synchrony of unconformities among basins and correlations with the $\delta^{18}O$ record. New Jersey provides a good record of Eocene shallow-water (neritic; <200 m) deposition. The New Jersey margin was subject to slow thermal subsidence (<10 m/m.y.) at that time (e.g., Steckler and Watts, 1979) and global changes in sea level should be reflected on this margin. We analyzed boreholes from Allaire State Park (Sugarman et al., 1991), Island Beach (Miller et al., 1994b), Atlantic County Girl Scout Council Camp 4 borehole (ACGS#4, Owens et al., 1988; Poore and Bybell, 1988; Miller et al., 1990), and Atlantic City (Miller et al., 1994a) to construct a detailed chronology of Eocene sequences on this passive margin (Figs. 1 and 2). This allows us to evaluate correlations with the inferred sea-level record of Haq et al. (1987) and the global $\delta^{18}O$ record.

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INTEGRATED STRATIGRAPHY

Unconformities were recognized in the cores as surfaces with irregular contacts, reworking, bioturbation, and major facies changes. We integrated lithostratigraphic, magnetostratigraphic, planktonic foraminiferal, and calcareous nannofossil biostratigraphic studies (ACGS#4: Poore and Bybell, 1988; Miller et al., 1990; Island Beach: Miller et al., 1994b; Atlantic City: Miller et al., 1994a; Allaire: Browning et al., 1996; Browning, 1996) to date the unconformities and their associated hiatuses. In general, sequences shallow upsection from basal glauconite sands to fine to very fine sandy clay deposited in outer neritic (100–200 m) paleodepths; otherwise, lithostratigraphic changes within sequences are subdued. Most of the lower to middle Eocene is carbonate rich; carbonate content decreased (from >20% to 5%) in the late-middle Eocene (~42 Ma). Benthic foraminiferal biofacies analysis was used to infer paleowater depths of generally 135 ± 25 m, ranging from 50 ± 25 m to 180 ± 25 m (Figs. 1 and 2). The time scale of Berggren et al. (1995) is used throughout. Ages, borehole depths, and general lithologic descriptions of the sequences are found in Table 1.

SEQUENCES, EUSTASY, AND THE $\delta^{18}O$ RECORD

We compare New Jersey Eocene sequences with third-order sea-level events of Haq et al. (1987) and the global deep-sea $\delta^{18}O$ record (Kennett and Stott, 1991; Pak, 1995) (Figs. 1 and 2). We recalibrated the Haq et al. (1987) record to the Berggren et al. (1995) time scale using the magnetostratigraphy and biostratigraphy provided in the "cycle chart." Whereas the chronology of the New Jersey Eocene sections can be directly tied to the GPTS and has a resolution typically of 0.5 m.y. or better, the Haq et al. (1987) record has resolution of about 1 m.y. or worse, considering differences in the biochronology presented.

Of the 14 sequence boundaries predicted by Haq et al. (1987) for the early to middle Eocene, 9 are resolvable on the New Jersey margin, and the other 5 appear to be com-

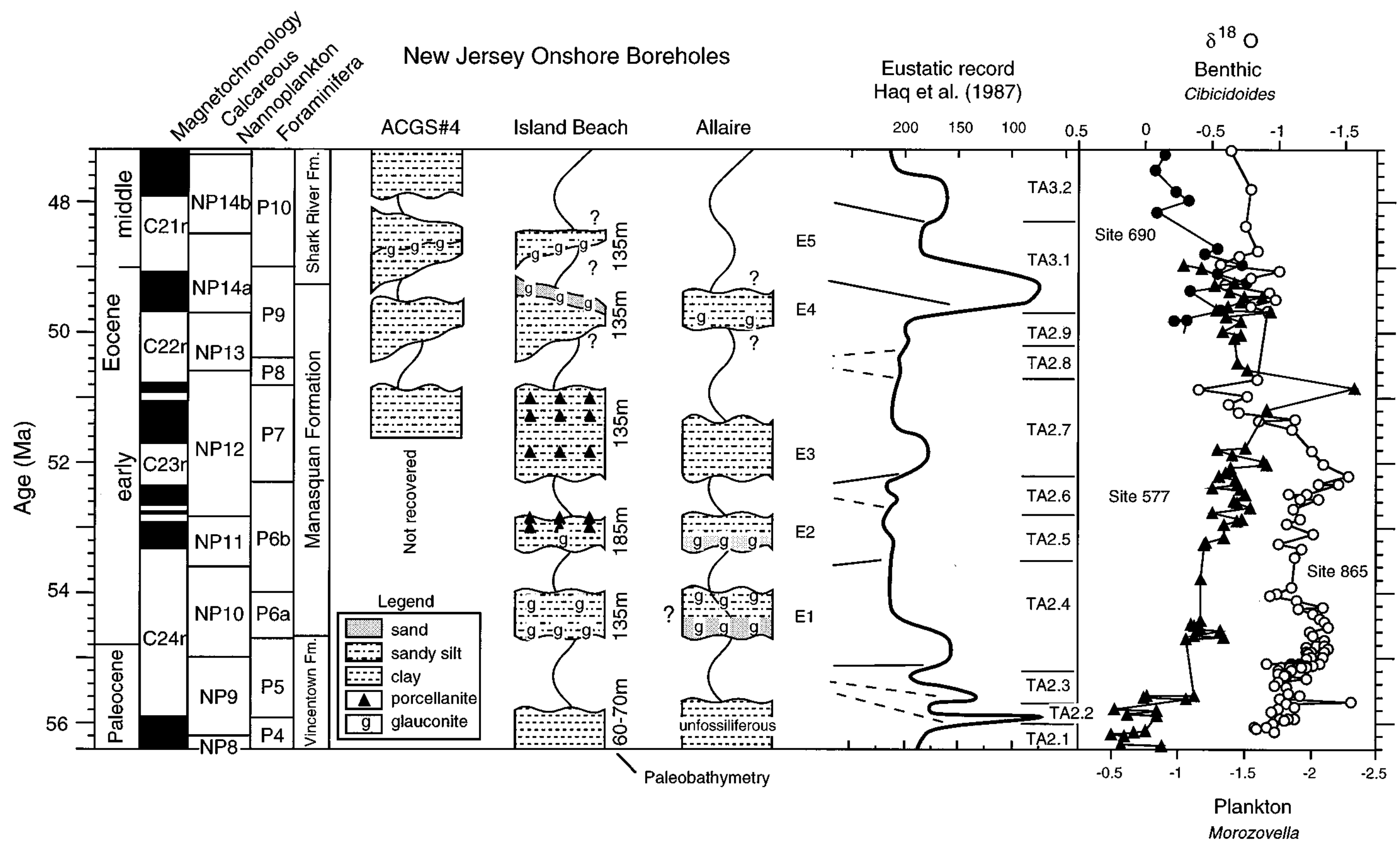

Figure 1. Distribution of sediments from lower Eocene of New Jersey coastal plain compared to eustatic record of Haq et al. (1987); benthic foraminiferal $\delta^{18}O$ record from southern (Site 690, Kennett and Stott, 1991) and Pacific oceans (Site 577, Pak, 1995; this study); and planktonic foraminiferal record from equatorial Pacific (Site 865, Bralower et al., 1995). Paleodepths are inferred using benthic foraminiferal biofacies analysis. E1 to E5 refers to Eocene sequences. Wavy lines indicate unconformities. See Figure 2 for key.

bined with others (Table 2). We note two differences between the Haq et al. (1987) record and ours (Figs. 1 and 2): (1) The TA3.1 sequence boundary was predicted by Haq et al. (1987) to be at the C22r-C22n boundary. We suggest that this major unconformity is associated with a major facies change and sea-level lowering at the top of C22n. (2) Two surfaces, with no discernible hiatuses in New Jersey at the lower-middle Eocene boundary, have no correlative predicted sea-level lowerings (~49.6 Ma at Island Beach; ~48.7 Ma at ACGS#4). We conclude that there is a favorable comparison between New Jersey Eocene sequences and the Haq et al. (1987) record, although the New Jersey record is better dated.

We also evaluate potential relationships between inferred ice-volume changes and unconformities on the New Jersey coastal plain. Covariance of tropical and benthic $\delta^{18}O$ records has been used by previous authors to infer ice-volume changes (Shackleton and Kennett, 1975; Miller et al., 1991). The magnitude of sea-level fall can be calculated by using the Pleistocene sea-level $\delta^{18}O$ calibration (0.11‰/10 m) of Fairbanks and Matthews (1978). We compare benthic foraminiferal (*Cibicidoides*) $\delta^{18}O$ records from Deep Sea Drilling Project and Ocean Drilling Program Sites 527 (Atlantic; Shackleton et al., 1984), 577 (Pacific; Pak, 1995; this study), 689 (southern; Kennett and Stott, 1991), and 690 (southern; Kennett and Stott, 1991) with a surface-dwelling planktonic foraminiferal (*Morozovella* spp.) $\delta^{18}O$ record from tropical Pacific Site 865 (Bralower et al., 1995; Figs. 1 and 2).

1. The lowest $\delta^{18}O$ values occurred in global deep waters in the early Eocene, a time in which water depths in New Jersey reached their maximum of ~180 m (Fig. 1). Lower Eocene unconformities on the New Jersey coastal plain do not correlate with increases in the $\delta^{18}O$ record. In particular, there are no $\delta^{18}O$ increases associated with the hiatuses between 55.9 and 54.4 Ma, 54.0 and 53.4 Ma, and 52.9 and 52.3 Ma. Changes in ice volume cannot be readily invoked to explain these early Eocene hiatuses.

2. Relationships between sequence boundaries and $\delta^{18}O$ in near the early-middle Eocene boundary are unclear due to insufficient sampling of oxygen isotopic records (Figs. 1 and 2).

3. Two early-middle Eocene hiatuses apparently correlate with benthic and planktonic foraminiferal $\delta^{18}O$ increases (48 Ma, covariance of 0.2‰, 18 m sea-level fall; 46.5–44 Ma, covariance of 0.3‰, 27 m sea-level fall), although additional isotopic data are needed to confirm this.

4. Two late-middle Eocene hiatuses correlate with benthic and planktonic foraminiferal $\delta^{18}O$ increases (43–41 Ma, covariance of 0.25‰, 23 m sea-level fall; and 40 Ma, covariance of 0.3‰, 27 m sea-level fall) (Fig. 2). The unconformity represented by the hiatus between 43 and 41 corresponds to a large water depth drop on the coastal plain of 40 m to as much as 100 m, and a change in lithofacies from carbonate mud dominated to siliciclastic sand dominated (Fig. 2).

DISCUSSION

What caused the early Eocene inferred global sea-level changes is not clear. Close agreement between the New Jersey record and the Haq et al. (1987) eustatic curve suggests that early Eocene sequence boundaries are globally synchronous. We show that there is little correlation between the early Eocene New Jersey coastal plain hiatuses and the $\delta^{18}O$ record (Figs. 1 and 2), and we cannot readily invoke glacioeustasy in this interval.

Although our correlations are consistent with an ice-free early Eocene, it is possible that small glacioeustatic variations have

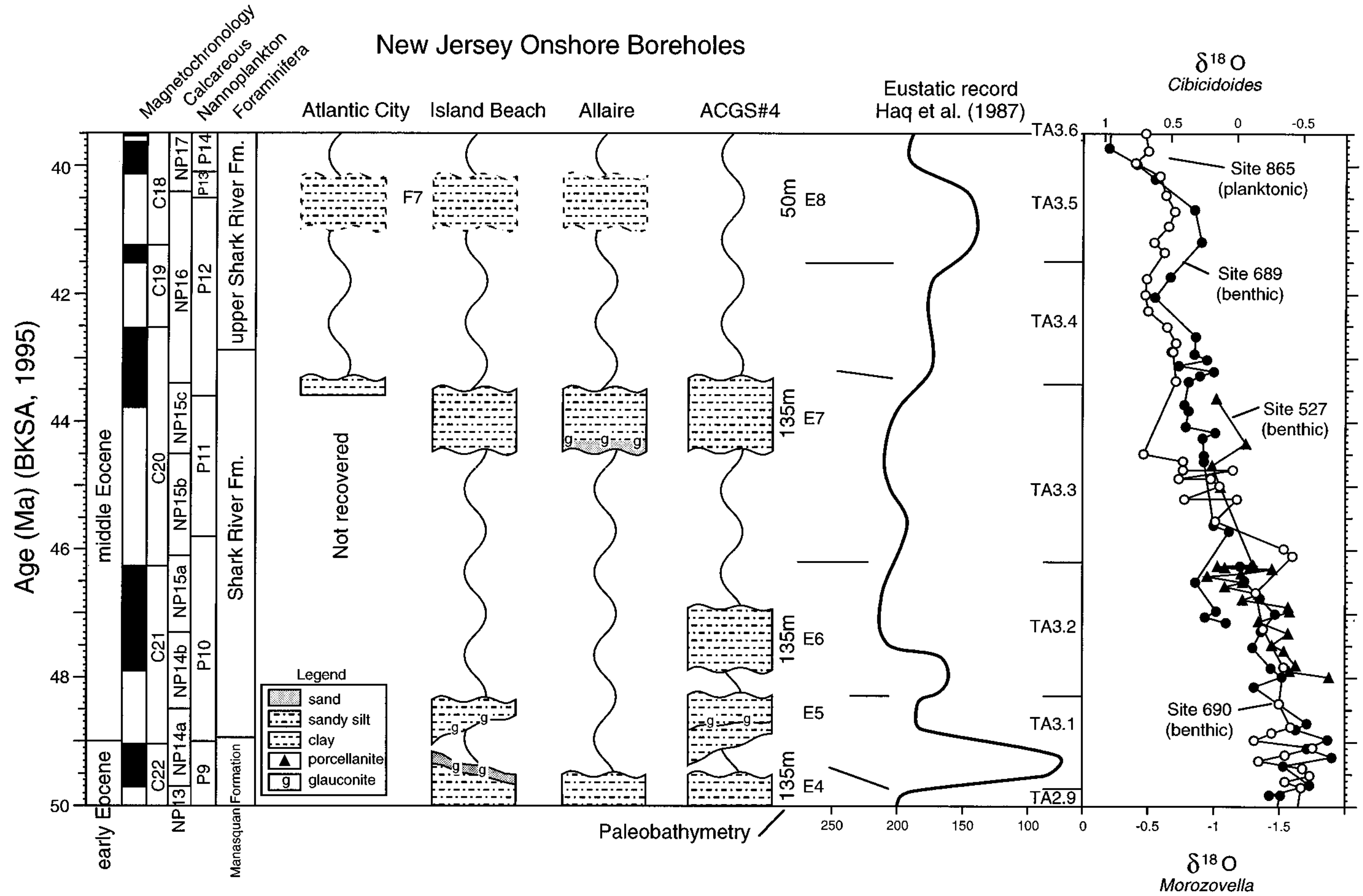

Figure 2. Distribution of sediments from middle Eocene of New Jersey coastal plain compared to eustatic record of Haq et al. (1987); benthic foraminiferal $\delta^{18}O$ record from southern (Site 689, Kennett and Stott, 1991) and South Atlantic oceans (Site 527, Shackleton et al., 1984); and planktonic foraminiferal record from equatorial Pacific (Site 865, Bralower et al., 1995). Paleodepths are inferred using benthic foraminiferal biofacies analysis. E4 to E8 refers to Eocene sequences. Wavy lines indicate unconformities. BKSA is Berggren et al.

gone undetected. The minimum detectable $\delta^{18}O$ change is ~0.2‰ (or higher with diagenesis and sparse sampling). Thus, a glacioeustatic change of ~18 m (~20% of present ice volume) is our detection limit using the isotopic records shown here and the Pleistocene calibration of 0.11‰/10 m. Although we consider the Pleistocene calibration to be appropriate, Miller et al. (1987) noted that the maximum $\delta^{18}O$-sea level calibration is fixed by the $\delta^{18}O$ of freezing ice to 0.055‰/10 m, yielding an outside detection limit of 36 m.

Although we do not ascribe early Eocene sea-level changes to ice volume, we estimate that early Eocene eustatic events were fairly large (>35 m) and rapid (<1 m.y.). Water depth changes between early Eocene sequences E1, E2, and E3 are on the order of 50 m (Fig. 1; 35 m corrected for water loading alone); these are minimal estimates because we do not sample the full range of water depth variation due to hiatuses and the absence of lowstand deposits (see also

TABLE 1. AGES, DEPTHS AND DESCRIPTION OF SEQUENCES FOUND IN NEW JERSEY COASTAL PLAIN BOREHOLES

Sequence	Age (Ma)	Island Beach Depth (ft/m)	ACGS#4 Depth (ft/m)	Allaire Depth (ft/m)	Atlantic City Depth (ft/m)	Lithology
E8	41.2-40.5	800-779 (243.8-237.4)	absent	204-175 (62.2-53.3)	1431-1390 (436.2-423.7)	Silty, glauconite and quartz sand; paleowater depth is 50± 25m
E7	44.5-43.4	846-800 (257.9-243.8)	844-792 (257.3-241.4)	234-204 (71.3-62.2)	TD-1431 (TD-436.2)	Silty, glauconite and quartz sand; paleowater depth is 130 ± 25m
E6	47.9-46.9	absent	880-844 (268.2-257.3)	absent	N.D.	Silty, glauconite and quartz sand; paleowater depth is 130 ± 25m
E5	48.6-48.3	857-846 (261.2-257.9)	905-880 (275.8-268.2)	absent	N.D.	Carbonate rich, slightly sandy clay; coarse glauconite sand at base, paleowater depth is 130 ± 25m
E4	49.9-49.6	876-857 (267.0-261.2)	920-905 (280.4-275.8)	243-234 (74.1-71.3)	N.D.	Porcellanitic clays with glauconite and quartz sand beds; paleowater depth is 130 ± 25m
E3	52.3-50.9	972-876 (296.3-267.0)	TD*-920 (TD-280.4)	280-243 (85.3-74.1)	N.D.	Slightly sandy clay with porcellanite beds; paleowater depth is 130 ± 25m
E2	53.4-52.9	1019.7-972 (310.8-296.3)	N.D.†	300-280 (91.4-85.3)	N.D.	Sandy, silty clay with porcellanite beds; paleowater depth is 180 ± 25m
E1	54.7-54.0	1075.5-1019.7 (327.8-310.8)	N.D.	absent	N.D.	Basal glauconite sand grading up to a glauconitic sandy silt; paleowater depth is 135 ± 25m

Note: The time scale of Berggren et al. (1995) is used throughout
* TD = Total Depth
† N.D. = No Data

TABLE 2. AGES OF HAQ ET AL. (1987) SEQUENCE BOUNDARIES COMPARED WITH NEW JERSEY COASTAL PLAIN SEQUENCE BOUNDARIES

Sequence	Age at base* (Ma)	Age on NJCP† (Ma)
TA2.2	56.0	55.9-54.7
TA2.3	55.7	55.9-54.7
TA2.4	55.2	55.9-54.7
TA2.5	53.5	54.0-53.4
TA2.6	52.8	52.9-52.3
TA2.7	52.2	52.9-52.3
TA2.8	50.7	50.9-49.9
TA2.9	50.2	50.9-49.9
TA3.1	49.7	49.6-48.6
TA3.2	48.1	48.3-47.9
TA3.3	46.2	46.9-44.5
TA3.4	43.4	43.4-42.6/41.2
TA3.5	41.5	43.4-42.6/41.2
TA3.6	39.5	40.5

Note: All ages recalibrated to the time scale of Berggren et al. (1995)
* Haq et al. (1987)
† NJCP = New Jersey coastal plain

Olsson and Wise, 1987). Changes in seafloor spreading rates or ridge length are too slow to explain these large, rapid (>10 m/m.y.) global sea-level changes (Donovan and Jones, 1979), although associated changes in production and destruction of ocean plateaus potentially can cause relatively large, rapid changes (Larson, 1991). We conclude that mechanisms for sea-level change are still not fully understood.

We cannot confirm that early-middle Eocene (43–49 Ma) sequence boundaries (Fig. 2) were due to glacioeustasy. Additional data are needed to confirm benthic and planktonic $\delta^{18}O$ increases at ~48 and 46.5–44 Ma (Fig. 2). Still, the limited isotopic evidence for early-middle Eocene glacioeustasy is consistent with evidence of glaciation in the South Shetland Islands, Antarctica, dated at 49 ± 5 Ma (Birkenmajer, 1988), although these tills could be attributed to alpine glaciation.

Late-middle Eocene evidence for glacioeustasy is clearer. Although a few workers (Prentice and Matthews, 1988) have argued for the existence of a continuous ice cap on Antarctica since the beginning of the middle Eocene, the oldest generally accepted evidence of glaciation puts it in the Oligocene, and a few studies extend ice sheets back to the late-middle Eocene (Barron et al., 1991). The isotopic and sequence records presented here (Fig. 2) indicate that ice-volume changes affected global sea level by at least 43–42 Ma.

CONCLUSIONS

We recognize and date nine lower to middle Eocene unconformities on the New Jersey coastal plain and correlate these to the $\delta^{18}O$ and Haq et al. (1987) records. Many of the 14 early to middle Eocene sequences summarized by Haq et al. (1987) appear to be global, although additional sections on other margins are needed to test this. New Jersey coastal plain hiatuses in the early Eocene do not match increases in the $\delta^{18}O$ record, and we conclude that this was a largely ice-free world. Early-middle Eocene (42–49 Ma) evidence for glacioeustasy is ambiguous. In contrast, good correlation between the $\delta^{18}O$ record and late-middle Eocene (younger than 42–43 Ma) hiatuses indicates a glacioeustatic control, and we conclude that this represents evidence of the first icecap on Antarctica.

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