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Notes

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ABSTRACT

The Eocene-Oligocene transition (between ca. 34 and 33.5 Ma) is the most profound episode of lasting global change to have occurred since the end of the Cretaceous. Diverse geological evidence from around the world indicates cooling, ice growth, sea-level fall, and accelerated extinction at this time. Turnover in the oceanic plankton included the extinction of the foraminifer Family Hantkeninidae, which marks the Eocene-Oligocene boundary in its type section. Another prominent extinction affected larger foraminifera, which resulted in the loss of some of the world's most abundant and widespread shallow-water carbonate-secreting organisms. However, problems of correlation have made it difficult to relate these events to each other and to the global climate transition as widely recorded in oxygen and carbon isotope records from deep-sea cores. Here, we report new paleontological and geochemical data from hemipelagic sediment cores on the African margin of the Indian Ocean (Tanzania Drilling Project Sites 11, 12 and 17). The Eocene-Oligocene boundary is located between two principal steps in the stable-isotope records. The extinction of shallow-water carbonate producers coincided with an extended phase of ecological disruption in the plankton and preceded maximum glacial conditions in the early Oligocene by ~200 k.y.

Keywords: mass extinction, Eocene, Oligocene, foraminifera, nannofossils.

INTRODUCTION

The Eocene-Oligocene boundary is defined at its Global Stratotype Section and Point (GSSP) at Massignano in Italy at a level that corresponds to the extinction of the Hantkeninidae (Premoli Silva and Jenkins, 1993). Unfortunately, carbonate preservation is poor in the type section, and stable-isotope stratigraphy is unreliable (Bodiselič et al., 2004), so there is uncertainty as to how the formal boundary level relates to global environmental changes. An important drill core through the Eocene-Oligocene boundary at Deep Sea Drilling Project (DSDP) Site 522 in the South Atlantic shows that the extinction of the Hantkeninidae preceded the most positive oxygen isotopic values, which correspond to the early Oligocene glacial maximum (Liu et al., 2004; Oberhänsli et al., 1984; Zachos et al., 1994), but the microfossils are rare and fragmentary because of dissolution (Poore, 1984). Other important sections

such as Sites 744 (Zachos et al., 1994) and 1218 (Coxall et al., 2005) do not contain hantkeninids. These considerations have led to recent calls for the formal Eocene-Oligocene boundary to be moved to a stratigraphic level or biostratigraphic horizon that is more easily correlated to the global climatic changes revealed by the isotope data (van Mourik and Brinkhuis, 2005).

It has long been known that a variety of long-lived and distinctive larger benthic foraminifera disappeared near the end of the Eocene (e.g., Glaessner, 1945). Following a detailed review of shallow-water carbonate sections in the Indian and Pacific Oceans, Mediterranean, and Americas, Adams et al. (1986) suggested that there had been a rapid mass extinction. Major groups to disappear included the Discocyclinidae, Asterocyclinidae, and some Nummulitidae. Because these groups were so abundant and widespread, it is plausible that their extinction had an effect on the global carbon cycle by con-

tributing to a sharp decline in shallow-water carbonate production (e.g., Kiessling et al., 2003). However, very few sections are complete across the boundary, and none has well-defined planktonic biostratigraphy, so it is unclear how rapid the extinction was and how it correlated to the stage boundary and/or global climate transition.

NEW DRILL CORES

We address these problems of correlation by analyzing a newly discovered Eocene-Oligocene boundary section in the Kilwa Group of Tanzania, drilled at Tanzania Drilling Project (TDP) Sites 11, 12, and 17. The sediments are hemipelagic clays with accessory debris flows deposited in a bathyal outer-shelf or slope environment in an estimated 300–500 m of water (Nicholas et al., 2006, 2007). The area has subsequently been uplifted, and the sedimentary succession is exposed on land. Analysis of organic

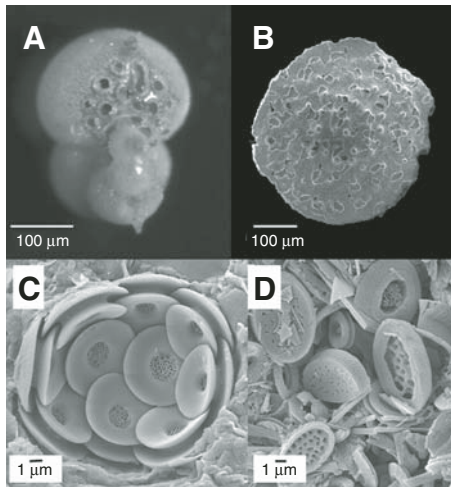


Figure 1. Microfossils from Tanzania Drilling Project (TDP) Sites 12 and 17 showing excellent preservation. **A:** Planktonic foraminifer *Cribrohantkenina inflata* (sample TDP17/39/4, 31–39 cm) showing typical “glassy” transparent test (taken in reflected light with Leica DFC 480 camera mounted on a Leica MZ 16 microscope using Earth Basic image software, exposure 180 ms). **B:** Scanning electron microscope (SEM) image of juvenile larger benthic foraminifer *Discocyclina* (sample TDP17/39/4, 31–39 cm). **C:** SEM of coccosphere of *Cyclicargolithus floridanus* (sample TDP 12/47–2). **D:** SEM of *Pontosphaera multipora* and other coccoliths (sample TDP 12/26/2, 62 cm).

biomarkers (van Dongen et al., 2006) shows that the Kilwa Group clays have never been deeply buried. They are characterized throughout by excellent preservation of carbonate microfossils (foraminifera and nannofossils) (Fig. 1); hence, the material is ideal for geochemical analysis (Pearson et al., 2001, 2007). The cores also contain larger foraminifera that were transported across the narrow continental shelf to the site of deposition, both as adult specimens in debris flows and as juveniles dispersed through the background clay sediment (Fig. 1B).

Correlation between the sites was achieved using a series of microfossil markers, which allowed us to construct a composite depth scale. We used a combination of biostratigraphic

datums and geochemical tie-points to generate an age model and correlate the record to deep-sea sites (see the GSA Data Repository¹). The age model is on the time scale of Berggren et al. (1995) with the E/O boundary at 33.7 Ma. A minor unconformity occurs in the lowermost Oligocene at the two more northerly sites (TDP 17 and 11), resulting in ~12 m and 3 m of eroded or missing section, respectively. The southerly site (TDP Site 12) appears complete across the Eocene-Oligocene boundary, which occurs in monotonous mudstone facies.

BIOTIC TURNOVER

Detailed studies of the microfossil biostratigraphies will be published elsewhere but can be summarized here. The Shannon diversity index for planktonic foraminifera (Fig. 2B)

¹GSA Data Repository item 2008042, age model, stable isotope data, and platinum group element data, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

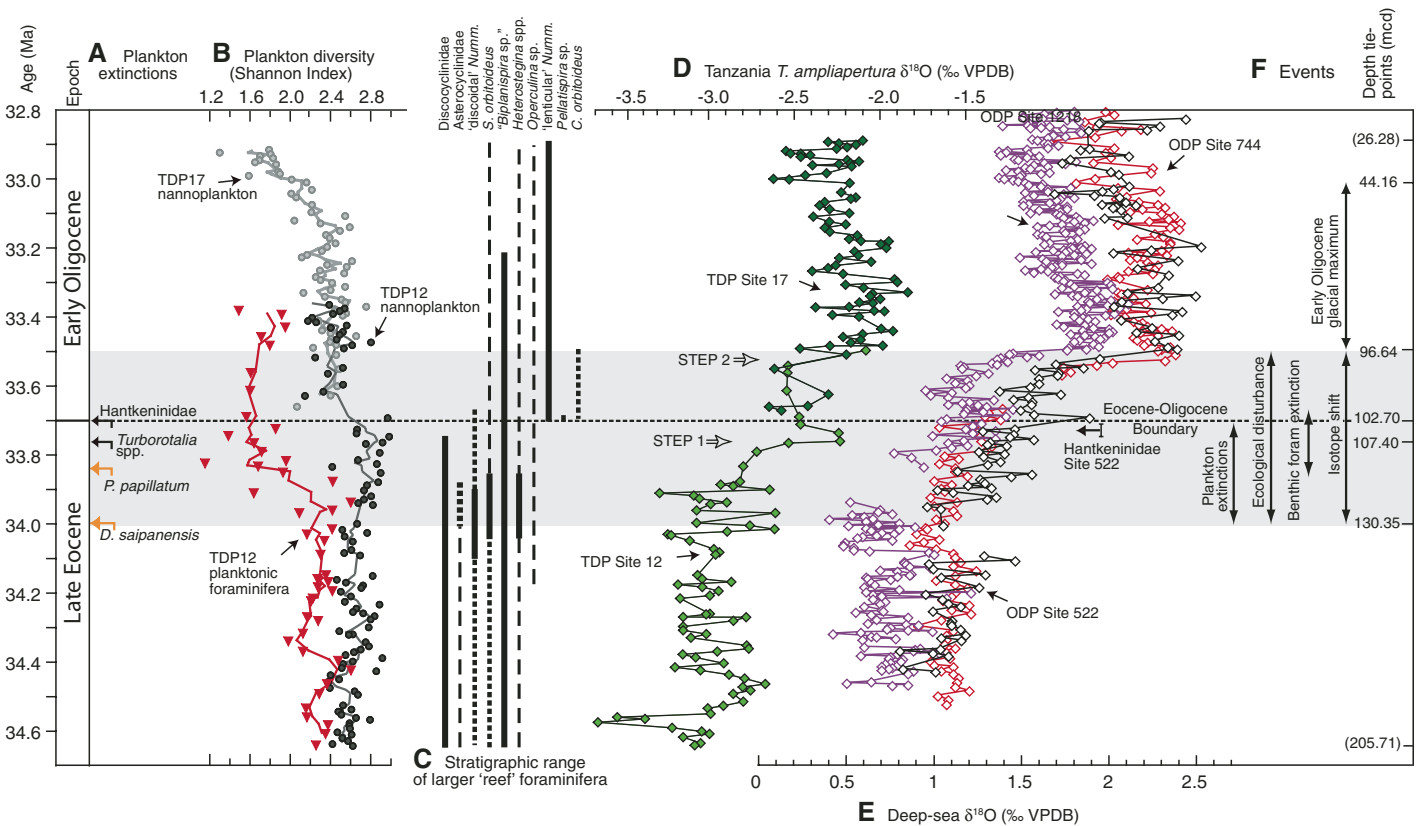


Figure 2. Biotic and geochemical events across Eocene-Oligocene boundary compared to deep-sea records. **A:** Plankton extinction levels. **B:** Shannon diversity index for planktonic foraminifera (red diamonds, Tanzania Drilling Project [TDP] Site 12) and calcareous nannofossils (black circles, TDP Site 12; gray circles, TDP Site 17; lines show three-point moving average). **C:** Chronostratigraphic ranges of larger benthic foraminifera, compiled from TDP Sites 11, 12, and 17. Legend: thick bars = common, thick dotted bars = frequent, thin dashed lines = rare, *Numm* = *Nummulites*, *S. orbitoideus* = *Spiroclipeus orbitoideus*, *C. orbitoideus* = *Cycloclipeus* sp. **D:** Planktonic foraminifer oxygen isotope record from *Turborotalia ampliapertura*, 212–150 μ (light-green diamonds, TDP Site 12; dark-green diamonds, TDP Site 17). VPDB—Vienna Pee Dee belemnite. **E:** Deep-sea benthic foraminifer isotope records (purple diamonds, Ocean Drilling Program [ODP] Site 1218 from Coxall et al. [2005]; red diamonds, ODP Site 744 from Zachos et al. [1994]; black diamonds ODP Site 522 from Zachos et al. [1994] with one point removed as suspect [S. Bohaty, 2007, personal commun.]). *Hantkenina* extinction with sampling bracket is from Poore (1984). **F:** Stratigraphical summary of events (mcd—meters composite depth).

shows moderately diverse assemblages up to ca. 34 Ma, after which diversity declined toward the Eocene-Oligocene boundary at 33.7 Ma. We recognize the boundary by the coordinated extinction of five planktonic foraminifer species in the Family Hantkeninidae (*Hantkenina* and *Cribrohantkenina*; see Coxall and Pearson, 2006). Apart from a single specimen from a higher level that may have been reworked, all five species disappear within a 25 cm sampling gap, equivalent to a sudden extinction in less than 5000 yr. This extinction is more sharply defined than at the GSSP (Coccioni, 1988), possibly because poor preservation and low abundances obscure the pattern there. The Eocene-Oligocene boundary event is preceded by the extinction or dramatic diversity reduction in the *Turborotalia cerroazulensis* group, which occurs 5.2 m below. In the age model for the Massignano stratotype, these extinction events are separated by ~65 k.y. (Berggren and Pearson, 2005). Other planktonic foraminifer events recorded in Tanzania that have been found elsewhere (Nocchi et al., 1986; Boersma and Premoli Silva, 1986; Molina et al., 2006) are the sudden dwarfing of *Pseudohastigerina micra*, which occurs precisely at the Eocene-Oligocene boundary, and a delayed diversification of *Dentoglobigerina* spp. in the lower Oligocene.

Calcareous nannoplankton show clear evidence of ecological disruption through the Eocene-Oligocene boundary interval. The extinctions of *Discoaster saipanensis* and *Pemma papillatum* are followed by a distinct shift toward less diverse assemblages across the boundary (Fig. 2B). These changes are mainly the result of stepwise abundance declines of warm-water taxa, some of which finally became extinct later in the Oligocene. The nannofossil diversity decline lags that seen in planktonic foraminifera.

The cores also record a series of extinctions and originations among the larger foraminifera (Fig. 2C). Specimens of *Discocyclina*, *Asterocyclina*, and a discoidal morphology of *Nummulites* are ubiquitous in the Eocene of Tanzania, up to and including the lower part of the cores described here, but they disappear close to the boundary level. The extinction of the Discocyclinidae seems to slightly precede the Eocene-Oligocene boundary. It may itself be preceded by the extinction of the Asterocyclinidae, although that group is generally rare in the cores, and so sampling effects limit our ability to precisely define the sequence of events. A discoidal morphotype of *Nummulites* is replaced by a new lenticular form very close to the boundary, and rare specimens of *Cycloclypeus* and (very briefly) *Pellatispira* also appear at this level. The record suggests that the turnover of larger foraminifera postulated by Adams et al. (1986) was relatively rapid

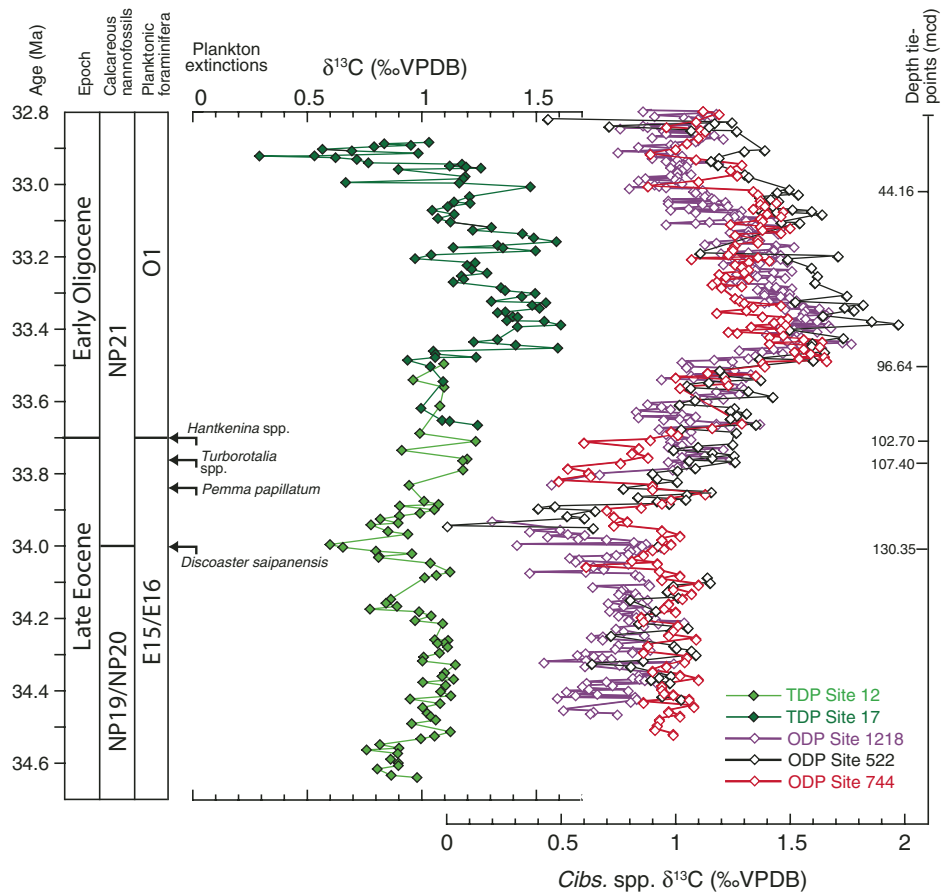


Figure 3. Carbon isotope stratigraphy across Eocene-Oligocene boundary in Tanzania compared to deep-sea records. VPDB—Vienna Pee Dee belemnite; ODP—Ocean Drilling Program; TDP—Tanzania Drilling Project; mcd—meters composite depth.

(<200 k.y.) but not instantaneous. Nevertheless, it constitutes a major crisis in carbonate platform ecology on a greater scale than had happened for tens of millions of years.

The extinction of such widespread and numerous shallow-water carbonate producers may itself have had a significant impact on Earth systems. If the extinctions were linked to a reduction in shelf-carbonate production rates, possible effects might have included a transient reduction in atmospheric CO₂, global cooling, increased ocean alkalinity, and a deepening of the oceanic carbonate compensation depth (CCD). All these are characteristic of the Eocene-Oligocene transition (Zachos et al., 2001; Coxall et al., 2005).

GEOCHEMISTRY AND GLOBAL CORRELATION

We constructed a stable-isotope stratigraphy from overlapping intervals of TDP Sites 17 and 12 using shells of the mixed-layer planktonic foraminifer *Turborotalia ampliapertura* (data given in the online GSA Data Repository, see footnote 1). The oxygen (Fig. 2D) and carbon (Fig. 3) isotope records are similar in form to

the most complete deep-sea benthic foraminifer isotope records (Oberhänsli et al., 1994; Zachos et al., 1996; Coxall et al., 2005). As in the deep-sea sites, the oxygen isotope record shows two main steps that lead in to the most positive values of the early Oligocene glacial maximum. The overall magnitude of the oxygen isotopic changes is less than shown by the benthic records, especially at the second main step, suggesting that high-latitude cooling as well as ice growth was responsible for generating the benthic records. This possibility is further examined using trace-element geochemistry by Lear et al. (2008).

No microtektites or other evidences for extraterrestrial impact were observed in any of our samples. To more fully investigate the possibility of impact, we analyzed platinum group element concentrations from 14 samples from TDP Site 12, but concentrations were close to average crust values throughout the succession (see online GSA Data Repository).

The first main step in the oxygen isotope record corresponds quite closely to the extinction level of the Discocyclinidae (benthic foraminifera) and *Turborotalia cerroazulensis*

and related species (planktonic foraminifera). A causal relationship, if any, between these events is unclear at present.

The extinction of the Hantkeninidae (planktonic foraminifera), which marks the Eocene-Oligocene boundary at the GSSP, is a sharply defined event that follows the extinction of the *Turborotalia cerroazulensis* group in sections as widely spaced as Tanzania (this study), Italy (Nocchi et al., 1986), Spain (Molina et al., 2006), the southeast Atlantic (Poore, 1984), and western equatorial Atlantic (Pearson and Chaisson, 1997). For the first time, we are able to place this event clearly in the plateau between the two main steps in the isotope records. This should enable improved correlation of the epoch boundary in a variety of geological settings, removing the need to shift the GSSP to some other section or point. The boundary corresponds to the climax of the marine extinctions and lies within an extended interval of severe global change that lasted ~500 k.y., as bracketed by the first nannofossil extinction (*Discoaster saipanensis*) and the beginning of the early Oligocene glacial maximum (see Fig. 2).

The Eocene-Oligocene transition marks a profound shift in global climate and marks the end to an extended period of predominantly “greenhouse” conditions on Earth that stretches back into the Mesozoic. The stepwise pattern of biotic events in the surface ocean and shelf seas, as recorded in the new cores, mirrors the pattern of global change. This pattern contrasts with sudden and catastrophic mass extinctions such as at the end-Cretaceous, suggesting that multiple causes, prolonged effects, and complex feedbacks between the geosphere and biosphere are necessary to explain the sequence of events that is only now becoming clear.

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