# Stable warm tropical climate through the Eocene Epoch

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## ABSTRACT

**Earth's climate cooled from a period of extreme warmth in the early Eocene Epoch (ca. 50 Ma) to the early Oligocene (ca. 33 Ma), when a large ice cap first appeared on Antarctica. Evidence from the planktonic foraminifer oxygen isotope record in deep-sea cores has suggested that tropical sea-surface temperatures declined by 5–10 degrees over this interval, eventually becoming much cooler than modern temperatures. Here we present paleotemperature estimates from foraminifer isotopes and the membrane lipids of marine Crenarcheota from new drill cores in Tanzania that indicate a warm and generally stable tropical climate over this period. We reinterpret the previously published isotope records in the light of comparative textural analysis of the deep-sea foraminifer shells, which shows that in contrast to the Tanzanian material, they have been diagenetically recrystallized. We suggest that increasingly severe alteration of the deep-sea plankton shells through the Eocene produced a diagenetic overprint on their oxygen isotope ratios that imparts the false appearance of a tropical sea-surface cooling trend. This implies that the long-term Eocene climatic cooling trend occurred mainly at the poles and had little effect at lower latitudes.**

**Keywords:** paleoclimate, paleotemperatures, diagenesis, foraminifera.

## INTRODUCTION

The sea-surface temperature (SST) gradient from the equator to the poles defines Earth's broad climatic belts. Whereas modern SSTs reach freezing in both hemispheres, there is ample evidence from "greenhouse" episodes of the geological past that subpolar seas were much warmer than they are now, and they sustained ice-free poles and produced warmer oceanic bottom waters than those that occur at the present day (Crowley and Zachos, 2000). Knowledge of how SST gradients have changed through time is central to understanding long-term global climate patterns, including modes of heat transport and the effects of different levels of radiative forcing (Pierrehumbert, 2002; Caballero and Langen, 2005). Oxygen isotope analysis of the shells of surface-dwelling planktonic foraminifers from past greenhouse episodes, such as the Cretaceous and Paleogene periods, has confirmed the evidence for warm polar seas, but it has also indicated surprisingly cool temperatures in the tropics (Shackleton and Boersma, 1981; D'Hondt and Arthur, 1996; Bralower et al., 1995; Dutton et al., 2005a, 2005b). However, several recent studies have cast doubt on the validity of much of the foraminifer data for quantitative climate reconstruction because of diagenetic effects (Norris and Wilson, 1998; Schrag, 1999, Wilson and Norris, 2001; Pearson et al., 2001; Wilson et al., 2002). If sufficient new calcite is added to plankton shells on the seafloor, or during early burial, the apparent "sea-surface" temperatures may reflect a combination of surface (warm) and seafloor (cold) signals. This could be particularly misleading in the tropics, where the maximum temperature differences between these environments occur (Schrag, 1999). However, the likelihood of such a diagenetic component has been disputed (Zachos et al., 2002; Pearson et al., 2002).

## MATERIALS AND METHODS

Here, we address this issue through stable isotope analysis of exceptionally well-preserved planktonic foraminifer assemblages from the Paleocene and Eocene of Tanzania, and we reassess the implications for the most important deep-sea sites. We conducted an onshore drilling program in Tanzania (Pearson et al., 2004, 2006; Nicholas et al., 2006) that enabled us to obtain new samples from a range of ages to supplement previous data from surface outcrops (Pearson et al., 2001). The drill cores also contain unoxidized sediment suitable for analysis of the membrane lipids of marine Crenarcheota, which allows us to employ the new $TEX_{86}$ index (tetraether index of 86 carbon atoms; Schouten et al., 2002, 2003; Hopmans et al., 2004; Jenkyns et al., 2004) as a second paleotemperature proxy.

Analysis of sedimentary facies, seismic data, paleogeography, nannofossil and foraminiferal assemblages of the Tanzanian sediments indicates that they were formed in open-ocean conditions, tens of kilometers from the paleoshoreline, in water depths of several hundred meters (Pearson et al., 2004, 2006; Nicholas et al., 2006). Organic biomarkers indicate an exceptionally low degree of thermal maturation (van Dongen et al., 2006). We attribute the excellent preservation state of the foraminifer shells to their encasement in relatively impermeable clay and their shallow maximum burial depths. The preservation is similar to that found in some other Paleogene and Cretaceous clay-rich shelf and slope settings (Norris and Wilson, 1998; Wilson and Norris, 2001; Pearson et al., 2001; Wilson et al., 2002).

The Paleogene sediment record in Tanzania, which comprises part of the recently described Kilwa Group (Nicholas et al., 2006), formed during a period of gradual subsidence on the East African margin. Onshore spot sampling and offshore industry wells show that it is remarkably complete (Nicholas et al., 2006). However, the exposed sediments are dissected by faults that were formed during their uplift and emplacement, which make it difficult to sample the entire succession on land. We employed mobile truck-mounted rigs to permit flexible sampling in what was often difficult terrain. Over four field seasons, we drilled 20 sites and cored about half the estimated Paleogene stratigraphy (Nicholas et al., 2006).

We measured the stable isotope ratios of foraminifera from 13 new samples of various ages to supplement the data already available from five outcrop samples (Pearson et al., 2001). We augmented these results with $TEX_{86}$ analyses taken from the same or adjacent samples where possible. Biostratigraphic age control is principally from planktonic foraminifers and nannofossils.

Analytical methods and all data are presented in the GSA Data Repository.[1] For the isotopic analyses, several species of foraminifera were analyzed from each sample and the most negative value was taken to calculate the seasonal maximum SST. The paleotemperature equation employed was that of Erez and Luz (1983) adjusted for global ice-volume changes of –0.75‰ for the Paleocene and early Eocene and –0.5‰ for the rest. We did not attempt to apply adjustments for other secular trends in seawater $\delta^{18}O$, regional variations in the oxygen iso-

[1]GSA Data Repository item 2007047, stable isotope and $TEX_{86}$ data and methods, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

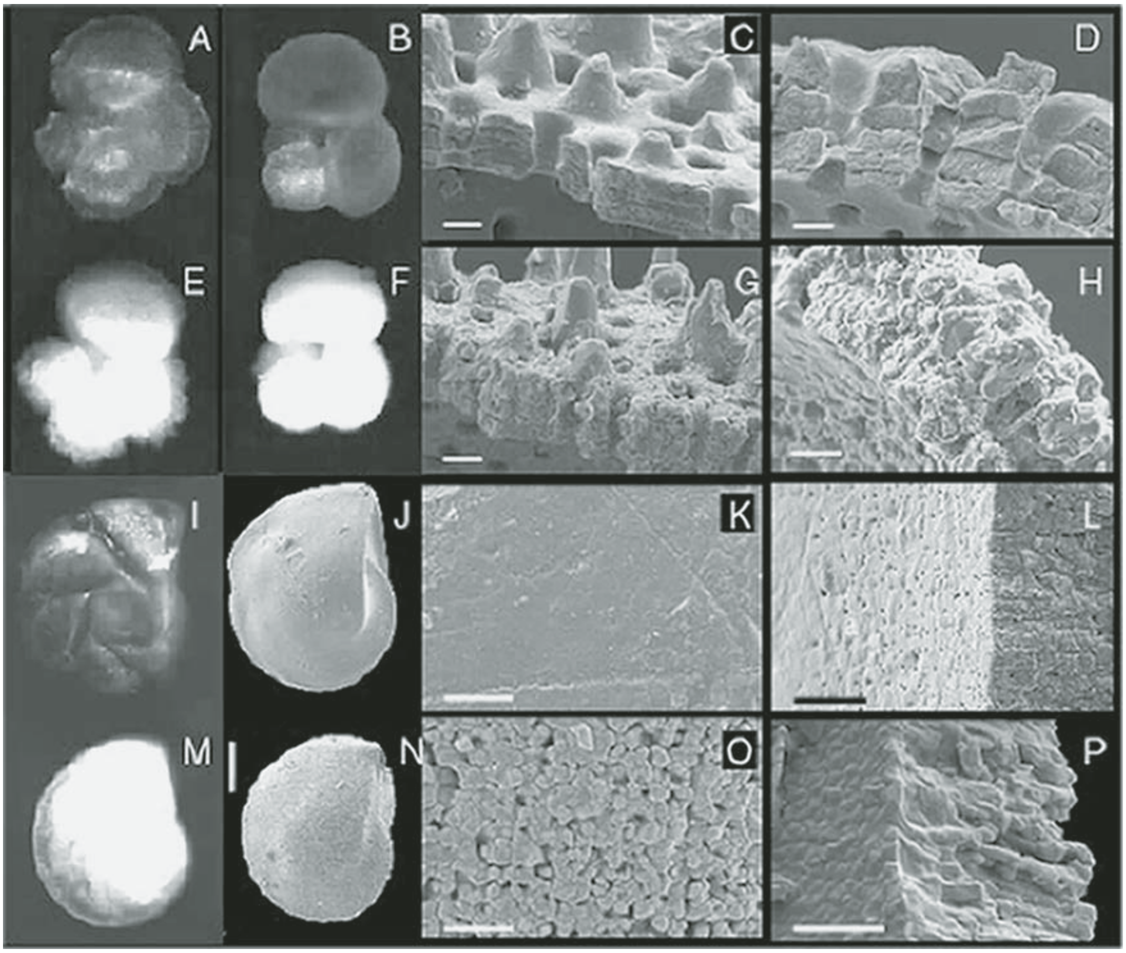


**Figure 1. Comparisons of preservation of planktonic foraminifer shells in Tanzania and deep-sea Ocean Drilling Program (ODP) Sites 865 and 1209. Tanzanian specimens are glassy and translucent under reflected light (RL) and show microgranular wall texture under scanning electron microscope (SEM). Deep-sea specimens are chalky and opaque under RL and show pervasive diagenetic recrystallization under SEM. A: *Morozovella subbotinae*, Tanzania, RL, sample TDP7A/64–1, 50–65 cm. B: *Subbotina triangularis*, Tanzania, RL, sample TDP7A/64–1, 50–65 cm. C: *Morozovella subbotinae*, Tanzania, deliberately broken specimen showing internal wall layering and biogenic pustules on surface, SEM, sample TDP7A/64–1, 50–65 cm. D: *Subbotina triangularis*, Tanzania, deliberately broken specimen showing internal wall layering, SEM, sample TDP7A/64–1, 50–65 cm. E: *Morozovella subbotinae*, Site 865, RL, sample 865C/12H-5, 110–113 cm. F: *Subbotina triangularis*, Site 865, RL, sample 865C/12H-5, 110–113 cm. G: *Morozovella subbotinae*, Site 865, deliberately broken specimen showing internal micron-scale recrystallization and replacement of surface pustules by large crystals, SEM, sample 865C/12H-5, 110–113 cm. H: *Subbotina* sp., Site 1209, deliberately broken specimen showing internal recrystallization and partial replacement with large (>5 μm) crystals, SEM, sample 1209A/17H-01W, 48–50 cm. I: *Lenticulina* sp., Tanzania, RL, showing reflective surface and transparent view of internal chamber partitions, sample TDP7A/64–1, 50–65 cm. J: *Lenticulina* sp. (same specimen), SEM, showing smooth test surface. K: *Lenticulina* sp. (same specimen), SEM, showing smooth surface on micron scale. L: *Lenticulina* sp. (same specimen), SEM, broken wall showing fine pore channels and well-preserved wall. M: *Lenticulina* sp., Site 865, RL, showing nearly opaque test, sample 865C/12H-5, 110–113 cm. N: *Lenticulina* sp., same specimen, SEM, showing test surface. O: *Lenticulina* sp., same specimen, SEM, showing micron-scale crystals on outer surface. P: *Lenticulina* sp., same specimen, SEM, broken wall showing internal recrystallization. Scale bars for wall texture views (C, D, G, H, K, L, O, P) = 10 microns. For other views (A, B, E, F, I, J, M, N) scale bar = 100 microns.**

tope ratio of seawater, or differing carbonate ion concentrations, because these factor are not sufficiently well known. The paleotemperature equation for the $TEX_{86}$ proxy was based on data from Holocene core top sediments (Schouten et al., 2002). Because the measurements presented here were beyond the range of the calibration set, it was necessary to extrapolate the calibration to derive SSTs. The relationship between $TEX_{86}$ and SST may not be linear, so we followed the approach of Schouten et al. (2003), in which the extrapolation is made using only data from Holocene sediments with SSTs >20 °C.

## FORAMINIFER SHELL PRESERVATION

The deep-sea sites with the most complete multispecies tropical isotope records are Ocean Drilling Program (ODP) Sites 865 and 1209, both from the Pacific Ocean (Bralower et al., 1995; Dutton et al., 2005a, 2005b). Foraminifera from these sites and Tanzania were examined using reflected light (RL) and scanning electron microscopy (SEM) at high resolution to determine the preservation state of the shells (Fig. 1). The Tanzanian specimens are translucent and reflective under the light microscope, giving them a "glassy" appearance. This feature contrasts with the opaque, chalky white shells from both deep-sea sites. At low magnification with SEM, the shells reveal comparable features of the wall surfaces such as pores, interpore ridges, and other ornamentation. At high resolution, however, the deep-sea sites both show a pervasive texture of equant crystallites, typically 1 μm in diameter, with obvious crystal faces. This contrasts with the well-preserved Tanzanian specimens, which have microgranular textures similar to unaltered modern shells (see Hemleben et al., 1989). Although the deep-sea foraminifers from Sites 865 and 1209 have been described as well preserved (Bralower et al., 1995; Dutton et al., 2005a, 2005b), our observations indicate that they have been wholly recrystallized (i.e., replaced with neomorphic calcite). They also have suffered from partial dissolution and overgrowth by larger diagenetic crystals on their surfaces, especially at Site 1209.

Not only would recrystallization of the deep-sea foraminifer shells in cold seafloor conditions be expected to bias oxygen isotope paleotemperature estimates toward unrealistically cold temperatures, it would also reduce the isotopic differentials between different species from different habitats (Pearson et al., 2001). For each of our samples, we analyzed a range of different species that would have lived at different depths in the water column and at different times of year. We note that in every case the Tanzanian assemblages have much larger isotopic differentials between species than is typically reported from deep-sea sites. Although comparisons between different locations can never be definitive, the contrast in interspecies differentials supports the notion of over 50% diagenetic component in the deep-sea data (Pearson et al., 2001).

## RESULTS AND DISCUSSION

Our SST estimates from both Tanzanian stable isotopes and $TEX_{86}$ measurements are consistently warmer than modern (Fig. 2). Although both methods have associated uncertainties, the degree of concordance between them lends confidence to a quantitative interpretation of the record. Maximum SSTs are mostly >30 °C, a temperature that is rarely reached in the modern open ocean, and other areas would have been warmer still (Huber and Sloan, 2001). A striking feature of the record is the relative constancy in implied SSTs from the early Eocene "climate optimum" (ca. 52 Ma) to the early Oligocene. We find no evidence for substantial SST cooling, such as has been argued for many years on the basis of the deep-sea planktonic isotope data (Shackleton and Kennett, 1975; Bralower et al., 1995; Dutton et al., 2005b). The late Eocene and early Oligocene values may indicate slightly cooler temperatures, but the data could equally be interpreted as resulting from the effect of a small amount of additional ice on the planet at these times. The Paleocene and earliest Eocene data may indicate a

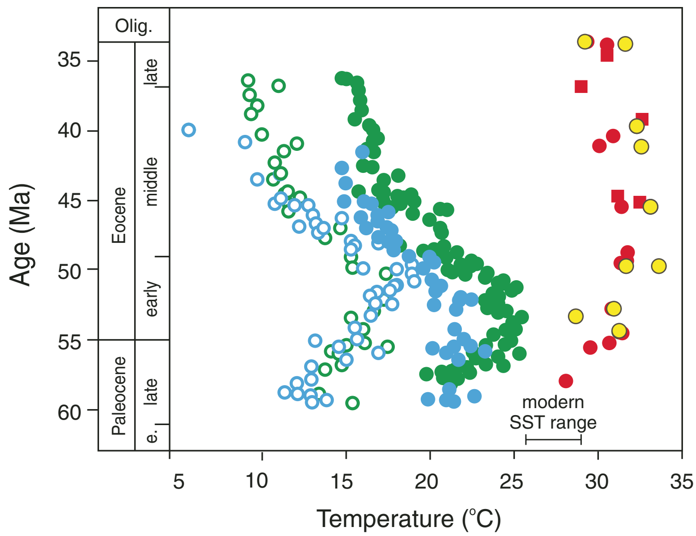


**Figure 2. Tanzanian and deep-sea paleotemperature estimates from foraminifer oxygen isotope ratios and $TEX_{86}$ analyses. Modern seasonal temperature range from offshore Tanzania is shown for comparison. Open circles—benthic foraminifers (green—Site 865; blue—Site 1209); closed circles—surface-dwelling planktonic foraminifers (green—Site 865; blue—Site 1209); red closed circles—new Tanzania planktonic foraminifer data from drill cores; red closed squares—Tanzanian planktonic foraminifer data from outcrops by Pearson et al. (2001); yellow circles—new Tanzanian $TEX_{86}$ estimates from drill cores. Note that oxygen isotope sea-surface temperature (SST) estimates are taken from lightest value given by an assemblage. Full list of species and their oxygen and carbon isotope data is given in GSA Data Repository (see text footnote 1). Note that two data points from Site 1209 have been omitted from figure because they were interpreted by Dutton et al. (2005b) as indicating a transient low-latitude water source at that site.**

tropical warming trend through this period, but more data are required to investigate this possibility.

Benthic foraminifer shells from the deep-sea sites show diagenetic textures similar to planktonic forms (Fig. 1). With caution, however, their oxygen isotope values can be interpreted as an attenuated bottom water temperature record, because both biomineralization and recrystallization would have occurred in contact with cold bottom or pore waters. The bottom water masses at Sites 865 and 1209 (oceanic intermediate water) were derived from high latitudes for most or all of the time (Bralower et al., 1995; Dutton et al., 2005b), and therefore their oxygen isotope records imply polar cooling through the Eocene.

Given the warm stable tropical climate indicated by the Tanzanian record, it is difficult to explain the planktonic oxygen isotope trends in the deep-sea sites by surface cooling; hence, we reinterpret the trends as reflecting a change in the seafloor diagenetic component. At both sites, there is a decline in the reported shell preservation up-section (Bralower et al., 1995; Petrizzo et al., 2005), which is supported by our own observations. It may be that the degree of diagenetic overprint at both Sites 865 and 1209 increased from the Paleocene through the Eocene as bottom waters became more undersaturated, colder, and more corrosive, and this effect may have been more severe at the deeper site (Site 1209).

The composite Tanzanian drill-core record is valuable because it contains excellently preserved foraminifer shells from a wide spread of ages through the Paleogene. Geochemical proxies for atmospheric carbon dioxide indicate high but declining levels over this interval (Pearson and Palmer, 2000; Pagani et al., 2005). Models of Eocene climate with high $CO_2$ concentrations (Huber and Sloan, 2001; Shellito et al., 2003) predict that tropical SSTs were significantly warmer than modern, which is in good agreement with our data and knowledge of the distributions of temperature-sensitive organisms (Adams et al., 1990). Moreover, warm tropical temperatures are necessary for the generation of active tropical cyclones, which has recently been proposed as a mechanism for sustaining ice-free poles in past greenhouse climates (Emanuel, 2002). Unlike the deep-sea record, our data also imply substantial temperature gradients, from the sea surface to seafloor and equator to poles, such as those required to sustain deep-water convection. However, the data also provide a new challenge to climate model studies, which is to replicate polar cooling through the Eocene while SSTs in the tropics may have remained constant or only slightly reduced. A nonlinear decline in heat transport by tropical storms in response to cooling could be one such mechanism.

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