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Notes

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Katy E. Wilson[1], Mark A. Maslin[2], Melanie J. Leng[3,4], John D. Kingston[5], Alan L. Deino[6], Robert K. Edgar[7], and Anson W. Mackay[2]
[1]Department of Earth Sciences, University College London, London WC1E 6BT, UK
[2]Department of Geography, University College London, London WC1E 6BT, UK
[3]Centre for Environmental Geochemistry, Department of Geography, University of Nottingham, Nottingham NG7 2RD, UK
[4]NERC Isotope Geosciences Facilities, British Geological Survey, Nottingham NG12 5GG, UK
[5]Department of Anthropology, University of Michigan, 1085 S. University Avenue, Ann Arbor, Michigan 48109, USA
[6]Berkeley Geochronology Center, 2455 Ridge Road, Berkeley, California 94709, USA
[7]Farlow Herbarium of Cryptogamic Botany, Harvard University, Cambridge, Massachusetts 02138, USA

ABSTRACT

Late Cenozoic climate history in Africa was punctuated by episodes of variability, characterized by the appearance and disappearance of large freshwater lakes within the East African Rift Valley. In the Baringo-Bogoria basin, a well-dated sequence of diatomites and fluviolacustrine sediments documents the precessionally forced cycling of an extensive lake system between 2.70 Ma and 2.55 Ma. One diatomite unit was studied, using the oxygen isotope composition of diatom silica combined with X-ray fluorescence spectrometry and taxonomic assemblage changes, to explore the nature of climate variability during this interval. Data reveal a rapid onset and gradual decline of deepwater lake conditions, which exhibit millennial-scale cyclicity of ~1400–1700 yr, similar to late Quaternary Dansgaard-Oeschger events. These cycles are thought to reflect enhanced precipitation coincident with increased monsoonal strength, suggesting the existence of a teleconnection between the high latitudes and East Africa during this period. Such climatic variability could have affected faunal and floral evolution at the time.

INTRODUCTION

Cenozoic aridification and emergence of grassland habitats in East Africa were punctuated by periods of enhanced climate variability, coincident with global climate transitions (Trauth et al., 2005). These have been linked with precessionally driven ecosystem variability (Magill et al., 2013) and precipitation changes that resulted in the periodic appearance and disappearance of freshwater lakes within the East African Rift Valley (Deino et al., 2006; Ashley, 2007; Kingston et al., 2007). While climate transitions have also been connected to changes in hominin speciation and dispersal events (Maslin and Trauth, 2009), the influence of climatic variability on key periods of faunal and hominin evolution remains unclear. High-resolution terrestrial Pliocene paleoclimate archives are rare, and so the reconstruction of past climate in regions such as East Africa remains a challenge. The modern East Africa climate is driven by interactions between atmospheric convergence zones and regional factors (e.g., topography, coastal currents, and sea-surface temperature fluctuations), resulting in complex and locally variable climatic regimes. Annual rainfall variability is closely related to the seasonal migration of the Intertropical Convergence Zone and associated advection of Indian Ocean moisture, which generates a bimodal rainfall distribution (Nicholson, 2000). Additional rainfall, delivered to the western regions of East Africa during July and August, results from the convergence of the thermally unstable Congo airstream (ultimately derived from the Atlantic Ocean) at the Congo Air Boundary (CAB) (Fig. 1). However, questions remain about how these large-scale patterns have changed in the past.

In the central Kenya Rift (Fig. 1), a well-dated sediment sequence (Barsemoi diatomites) offers an opportunity to study terrestrial climate variability coincident with both the intensification of Northern Hemispheric glaciation (ca. 2.7–2.5 Ma) and the evolution of the genus *Homo* (Hill et al., 1992). Exposed within the Chemeron Formation in the Tugen Hills (0°20′–1°N, 36°5′E; Fig. 1), five diatomite units, composed almost exclusively of intact and fragmented siliceous diatom frustules (~95% by volume), are interbedded with fluviolacustrine sediments and volcanic ashes. Diatomites vary in thickness between 3 and 8 m and are intermittently exposed in the Barsemoi, Ndau, and Kapthurin river drainage systems (Fig. 1). The region is semiarid; mean annual rainfall is 600–900 mm on the rift valley floor and >1000 mm in the adjacent highlands. Potential evaporation on the valley floor is in excess of 2600 mm/yr. Following the criteria of Trauth et al. (2005), comparisons of floral changes indicate that the estimated depth of paleo–Lake Baringo could have exceeded 150 m (Kingston et al., 2007). Assuming a modern rift topography, GIS modeling indicates that the possible extent of a 150-m-deep lake could have spanned the width of the Rift Valley (Goble et al., 2008). Paleomagnetic reversal stratigraphy and astrochronologically tuned $^{40}Ar/^{39}Ar$ ages obtained for the intercalated ash layers constrain the chronology of the diatomites to 2.68–2.55 Ma (Deino et al., 2006). Each diatomite coincides with a precession-induced maximum in boreal summer insolation at 30°N, implying a link between insolation forcing of tropical monsoon intensity and increased lake levels in the Baringo Basin (Kingston et al., 2007).

METHODS AND RESULTS

Here we focus on Barsemoi diatomite #4 (790 cm thick), which includes a distinct, datable ash layer (160 cm above base). Its onset is marked by a sharp contact with underlying fluvial sediments, and the upper 150 cm are characterized by a transition from a relatively pure (~95% diatoms) laminated diatomite to diatomaceous clay (~60% diatoms). Within each diatomite, an absence of littoral diatom species implies an abrupt onset of deep-water conditions conducive to diatomite deposition that persisted for much of the lake phase, followed by a gradual shift toward shallower waters as the lake regressed (Kingston et al., 2007). $^{40}Ar/^{39}Ar$ dating of two bordering ash layers (Deino et al., 2006) indicate that the lake persisted for 11 k.y. (2.617–2.606 ± 0.005 Ma), coincident with the early part of glacial Marine Isotope Stage (MIS) 104 (2.614–2.595 Ma). Having only one datable ash layer within unit 4, a linear sedimentation rate is assumed (72 cm/k.y.). However, natural lake cycles often result in contrasting sedimentation patterns, leading to thin (transgressive) and thick (regressive) sediment accumulations; it is thus important to consider the impact of non-uniform sedimentation on the age model for unit 4 (see the GSA Data Repository[1]).

[1]GSA Data Repository item 2014338, additional information on chronology, geochemistry, and mass-balance contamination corrections, ODP 721/722 Ti/Al data and spectral analysis (including a periodicity plot, Figure DR1), is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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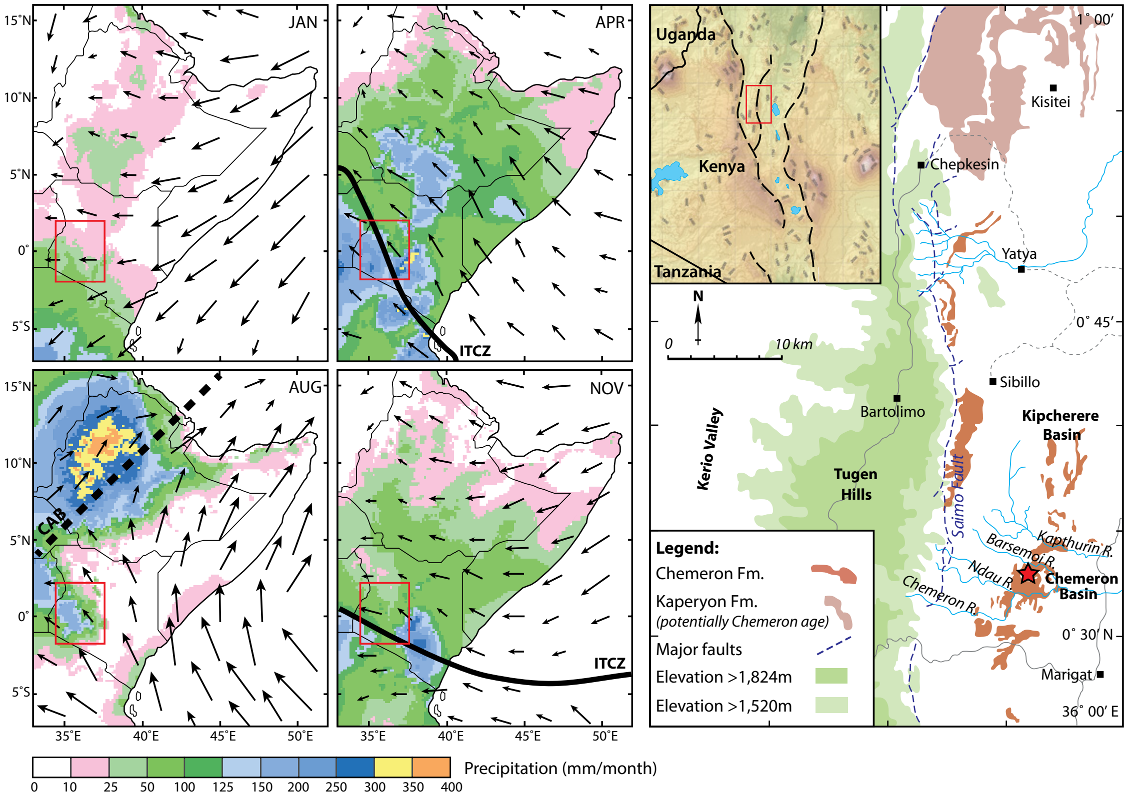

Figure 1. Seasonal climatology of East Africa comprising National Centers for Environmental Prediction–derived average monthly precipitation values based on observational measurements for years 1920–1980, overlain by 925 hPa wind data (Kalnay et al., 1996) and approximate positions of the Intertropical Convergence Zone (ITCZ) and Congo Air Boundary (CAB). Solid red boxes mark area detailed on inset map. Red dashed box in inset map is location of the Tugen Hills within the central Kenya Rift. Right panel shows areas of exposed Chemeron Formation (Fm.) sediments (modified from Kingston et al., 2007). Red star is location of sampling site for this study.

To evaluate precipitation and evaporation changes associated with this lake event, we developed paired oxygen isotope ($\delta^{18}O_{diatom}$) and X-ray fluorescence (XRF) measurements of biogenic silica, combined with taxonomic changes in diatom assemblage. Samples (n = 47) were purified using a modification of published chemical and physical methods (Morley et al., 2004; Wilson et al., 2014) and analyzed for $\delta^{18}O_{diatom}$ at the Stable Isotope Facility (NIGL) at the British Geological Survey using step-wise fluorination (Leng and Sloane, 2008). Within-run analytical reproducibility of the diatomite $\delta^{18}O$ samples was 0.34‰ (n = 4), whereas between-run reproducibility of the internal NIGL BFC diatomite standard was 0.22‰. XRF was used to assess the geochemistry of the cleaned material in order to assess levels of remnant contamination. $\delta^{18}O_{diatom}$ values were then corrected ($\delta^{18}O_{modeled}$) through the development of a mass-balance model based on the identification of two contaminants (tephra and clay) using principal components analysis (for the complete methodology, see Wilson et al., 2014).

DISCUSSION

Within lacustrine environments, $\delta^{18}O_{diatom}$ varies as a function of temperature and the isotopic composition of ambient lake water ($\delta^{18}O_{lakewater}$) at the time of silicification (Leng and Barker, 2006). In tropical regions, where seasonal temperature change is minimal, $\delta^{18}O_{diatom}$ predominantly reflects $\delta^{18}O_{lakewater}$, which is controlled by the isotopic composition of regional precipitation (δ_p) and the relative balance between local precipitation and evaporation (Leng and Barker, 2006). The $\delta^{18}O_{modeled}$ record (Fig. 2) exhibits regular negative excursions of ≤5‰ that occur every ~1400–1700 yr (mean frequency = 1460 ± 480 yr, n = 6; spectral analysis indicates a dominant periodicity of 1650 yr; see the Data Repository). Even when non-uniform sedimentation rates are considered, the estimated frequency of these excursions does not vary greatly (mean frequency = 1360 ± 380 yr). Negative $\delta^{18}O_{modeled}$ excursions represent freshening events that may have resulted from either (1) periodic changes in the dominant moisture source to the region (i.e., Indian Ocean versus African rainfall sources), or (2) relative local increases in precipitation, including a reduction in $\delta^{18}O$ caused by the amount effect (Dansgaard, 1964; Barker et al., 2001). To invoke a change in moisture source, a local increase of isotopically depleted precipitation is required. Studies of modern δ_p indicate that a distinct difference in samples from Kenya ($\delta^{18}O$ of –2.5‰ ± 2.4‰, n = 181) and Ethiopia ($\delta^{18}O$ of –0.2‰ ± 1.8‰, n = 165) is a function of different moisture sources (Levin et al., 2009). Wet season rainfall in Kenya is predominantly associated with an Indian Ocean source while the Ethiopian Rift, north of the CAB (Fig. 1), is also influenced by isotopically heavier, continentally transpired precipitation brought by the West African monsoon, ultimately derived from the Atlantic Ocean (Levin et al., 2009). Given the requirement for more isotopically negative precipitation at Lake Baringo in the Pliocene, we suggest that the negative $\delta^{18}O_{modeled}$ excursions in our record do not result from changes in the local moisture source (e.g., related to variations in CAB position or changes in the West African monsoon). Assuming minimal cooling during Pliocene glacial stages, we propose that changes in $\delta^{18}O_{modeled}$ reflect fluctuations in the relative balance between input (precipitation, including amount effect) and output (evaporation) in the lake system. Thus, more positive $\delta^{18}O_{modeled}$ intervals may reflect periods of enhanced local evaporation, driven by dry season length and intensity. More negative $\delta^{18}O_{modeled}$ values imply a less pronounced dry season or enhanced local precipitation, which we suggest is associated with invigorated Indian Ocean monsoonal circulation inferred from Ti/Al data from Ocean Drilling Program (ODP) Site 721/722 (Fig. 2; Wilson, 2011). This interpretation is further supported by the timing of Barsemoi diatomite deposition, which coincides with increasing summer insolation at 30°N (Fig. 2). Models and proxy data suggest strong links among insolation, Indian Ocean sea-surface temperature, and monsoon strength (Prell and Kutzbach, 1992; Wang et al., 2005). After 2.610 Ma, summer insolation (30°N) decreases and local millennial-scale wet-dry cycles implied by our $\delta^{18}O_{modeled}$ record suggest enhanced climate variability (Fig. 2). The abrupt nature of the fluctuations between relatively wetter and drier conditions in paleo–Lake Baringo is similar to other lakes in East Africa (termed amplifier lakes) where lake levels respond rapidly to

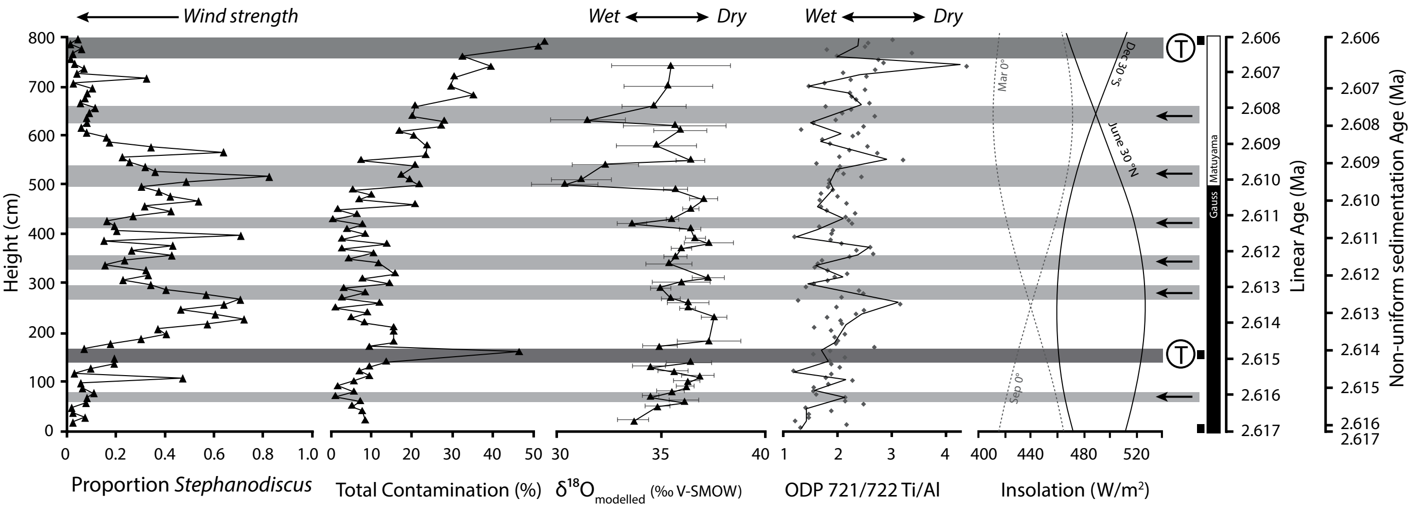

Figure 2. Compiled results from the analysis of diatomite unit 4 plotted against height and age (calculated for both linear and non-uniform sedimentation rates; see text). In all samples, the binomial proportion (p) of *Stephanodiscus* in a sample count has a 95% confidence interval of maximally p ± 0.05. Total contamination values are derived from X-ray fluorescence analysis and used to correct raw $\delta^{18}O$ values (V-SMOW—Vienna standard mean ocean water) for the presence of clay and/or tephra by mass-balance calculations (Wilson et al., 2014). Dark gray bars (labeled T) mark locations of known tephra layers within the sequence; light gray bars highlight negative excursions in the $\delta^{18}O_{modeled}$ record. Black squares highlight positions of $^{40}Ar/^{39}Ar$ dates (Deino et al., 2006). The ratio of Ti/Al from Ocean Drilling Program (ODP) Site 721/722 in the Arabian Sea is a proxy for lithogenic content, representing the eolian transport of terrigenous matter, controlled by Indian Ocean monsoonal circulation. Raw data (diamonds) are interpolated onto the lower resolution sampling grid of the $\delta^{18}O_{modeled}$ data using a cubic-spline interpolation (solid line).

moderate shifts in climate (Trauth et al., 2010). We propose that not only were there distinct episodes when lakes such as Baringo expanded and contracted on precessional time scales, but within these humid phases, climate, and thus lake extent, also exhibited millennial variability.

The diatom assemblage in unit 4 (Fig. 2) consists of two principal planktonic genera, *Aulacoseira* and *Stephanodiscus* (>97% in numbers), and variations in their relative abundance are moderately associated with $\delta^{18}O_{modeled}$ (Fig. 2; Kendall rank correlation, $\tau = 0.178$, $n = 42$, $p = 0.048$). Generally, more negative $\delta^{18}O_{modeled}$ values are associated with greater abundances of *Aulacoseira* (with the exception of ca. 2.610 Ma). In living populations, these groups flourish under contrasting hydrodynamic, nutrient, and light conditions (Talling, 1986). To sustain positive population growth, the more heavily silicified meroplanktonic *Aulacoseira* (mainly *A. agassizii, A. granulata*, and *A. nyassensis*) require stronger wind-generated turbulence in the upper water column retarding sinking losses than the less silicified euplanktonic *Stephanodiscus* [mainly the <30-μm-diameter *S.* aff. *Medius* and *S. astraea* v. *intermedia* sensu Gasse (1980)] (Kilham et al., 1986; Huisman and Sommeijer, 2002). Thus, variations in *Aulacoseira* and *Stephanodiscus* may be described as a function of windiness: *Aulacoseira* predominates under windier (and possibly cooler) conditions, whereas *Stephanodiscus* thrives in stratified waters (Gasse et al., 2002). The observed association between negative $\delta^{18}O_{modeled}$ values and *Aulacoseira* suggests that the lake underwent periods of enhanced precipitation and windiness.

Our diatomite #4 data reveal millennial-scale cyclicity (1400–1700 yr) similar to that of the Dansgaard-Oeschger (D-O) oscillations observed in high-resolution paleoclimate records during the last glaciation (MIS 2) (Bond et al., 1999). Our record is the first of its kind from a low-latitude lacustrine sequence, but it is not the only Pliocene record to exhibit such cyclicity. Marine and lacustrine sequences from the North Atlantic (Bartoli et al., 2006; Bolton et al., 2010) and Mediterranean regions (Kloosterboer-van Hoeve et al., 2006; Weber et al., 2010) also exhibit sub-Milankovitch-scale variations of 1–11 k.y. While the mechanisms driving millennial-scale variability remain unclear, D-O periodicities evident after ca. 2.88 Ma imply that the phenomenon is associated with the presence of ice following the intensification of Northern Hemisphere glaciation (Bartoli et al., 2006). Evidence for ice rafting during MIS 104 (Kleiven et al., 2002) further strengthens the interpretation that Earth's climate has oscillated on millennial time scales since the intensification of Northern Hemispheric glaciation at both high and low latitudes, and that the effects of this cyclicity propagated beyond the North Atlantic region, possibly via atmospheric teleconnections (Sirocko et al., 1996; Schulz et al., 1998).

CONCLUSIONS

Diatom stable isotopic and assemblage data from a Pliocene sediment sequence in the East African Rift Valley provide evidence for precessional-scale variations in paleo–Lake Baringo. During deep lake (humid) phases, millennial-scale variations in local hydrography occurred that we suggest reflect periods of enhanced precipitation. The rapid response of the lake to changes in local and regional climate could have contributed toward local environmental change during a threshold period in African faunal evolution. High-resolution records of terrestrial change to evaluate potential ecosystem response are required to further support this hypothesis.

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