Response of the East African climate to orbital forcing during the last interglacial (130–117 ka) and the early last glacial (117–60 ka)

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ABSTRACT

Variations in the temporal and spatial distribution of solar radiation caused by changes in Earth's orbit provide a partial explanation for observed long-term fluctuations in African lake levels. The understanding of causal links between insolation changes and lake-level fluctuations is essential for the design of models predicting future changes in the hydrological budgets and water supply in Africa. Here we present a record of climate change in East Africa between 175 and 60 ka. This time span includes the last interglacial (the Eemian, 130–117 ka), which may provide the closest analogue to the present interglacial. Assessments of the nature and timing of East African climate changes are based on lake-level fluctuations of Lake Naivasha (Kenya) inferred from sediment characteristics, diatom assemblages, and $^{40}Ar/^{39}Ar$ dating. Our results show dramatic alternation between deep, freshwater and shallow, highly alkaline lake conditions. The Lake Naivasha record demonstrates that periods of increased humidity in East Africa mainly follow precessional insolation forcing in spring, causing more intense April–May rains every 23 k.y.

Keywords: East Africa, lake sediments, Milankovitch, climate.

INTRODUCTION

Present African climate is mainly controlled by the strength of the African-Asian monsoonal circulation and the position and seasonal migration of the Intertropical Convergence Zone (Nicholson, 1996). Whereas most of the northern and southern part of the continent is characterized by monsoonal climates with summer rains and winter droughts, the main source of rainfall in equatorial East Africa is the Intertropical Convergence Zone (McGregor and Nieuwolt, 1998). The zone of maximum rainfall follows the latitudinal position of the overhead sun with a time lag of ~4–6 weeks resulting in two rainy seasons, the long rains around April–May and the short rains around October–November.

During the late Pleistocene, African climatic changes on time scales of thousands of years apparently were paced by periodic (23–19 k.y.) variations in insolation resulting from Earth's orbital precession (Rossignol-Strick, 1983; Kutzbach and Street-Perrott, 1985; Clemens et al., 1991). Low lake levels in northern and eastern Africa during the last glacial maximum (23–18 ka) that followed highstands ca. 15 ka are consistent with orbital forcing (Street and Grove, 1979; Gasse et al., 1989; Bonneville et al., 1990). A series of abrupt events of increased precipitation and temperature may reflect complex interactions between orbital forcing, atmosphere, ocean, and land-surface conditions (Gasse, 2000). Marine records (e.g., Rossignol-Strick, 1983; Clemens and Prell, 1990; deMenocal et al., 1993; Zahn and Pederson, 1991) as well as continental records (Gasse, 1977; Partidge et al., 1997) suggest antiphase changes in summer insolation and enhanced rainfall in the northern and southern monsoonal belts of Africa as predicted by orbital precession geometry (Berger, 1978). Detailed and well-dated records from equatorial Africa documenting pre–23 ka fluctuations of the intertropical convergence and convective rainfall on the equator are rare. These records suggest a period of high lake levels and increased humidity ca. 135 ka, well before the onset of the monsoon system (Butzer et al., 1969; Sturchio et al., 1993; deMenocal et al., 1993; Zahn and Pederson, 1991).

New high-resolution paleohydrological and radiometric age data from lake deposits and pyroclastic intercalations in the closed Naivasha basin (central Kenya Rift Valley) provide a detailed chronology of lake-level changes and East African climate between 175 and 60 ka (Fig. 1) (Trauth and Strecker, 1996). Together with the two most relevant African records from Lake Abhé in northern Ethiopia (ca. 75 ka to present; Gasse, 1977) and the Pretoria Saltpan in South Africa (ca. 200 ka to present; Partridge et al., 1997), the Naivasha lake history for the first time provides paleoclimate data in East Africa extending this far back in time. In addition, this record pro-

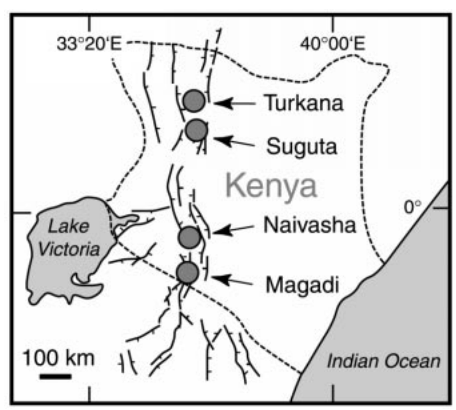

Figure 1. Map of Kenya Rift showing locations of Lake Turkana, paleo–Lake Suguta, Lake Naivasha, and Lake Magadi.

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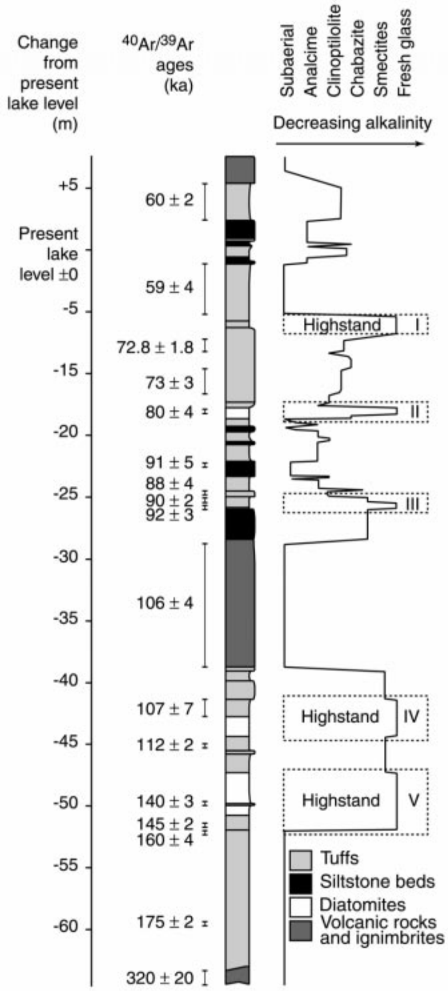

Figure 2. Sediment profile of Ol Njorowa Gorge showing major lithologic units and inferred lake-level fluctuations based on diagenetic mineral phases and diatomites.

vides data for a longitudinal transect of late Pleistocene climate-proxy records, now permitting evaluation of the timing of tropical climate response to orbitally induced insolation forcing across the equator.

METHODS

Situated at an elevation of 1890 m, Lake Naivasha is the highest freshwater lake of the rift (0°55′S, 36°20′E). Annual precipitation in the basin is 750 mm/yr, whereas potential evapotranspiration reaches 1600 mm/yr. The lake is fed by rivers draining the as much as 4000-m-high eastern rift shoulder, where rainfall exceeds 1200 mm/yr (Clarke et al., 1990). We analyzed a 60-m-thick sedimentary sequence in the Ol Njorowa Gorge at the margin of the Naivasha basin, which was incised and exposed after the last lake-level highstand ca. 10–9 ka (Washbourn-Kamau, 1977). The paleoecology of the basin was reconstructed using sedimentary characteristics and silica-algae (diatom) assemblages (Gasse, 1986). Bulk mineralogy was obtained from X-ray diffraction using standard techniques. Anorthoclase and sanidine phenocryst concentrates from several tuff beds (ignimbrites, air-fall tuffs, and reworked tuffs) and one lava flow were dated by the laser total-fusion (Deino and Potts, 1990; Deino et al., 1998) and laser (CO_2) incremental-heating $^{40}Ar/^{39}Ar$ dating methods (Sharp and Deino, 1996). Silicic pyroclastic deposits in the profile allow an evaluation of lake alkalinity by means of the state of alteration of volcanic glass and the presence of authigenic silicates (Utada, 1966; Surdam and Sheppard, 1978). Authigenic silicates such as zeolites and potassium feldspar are common in ephemeral water bodies in arid or semiarid regions, where high pH conditions result from concentration of sodium carbonate-bicarbonate due to evapotranspiration (Surdam and Sheppard, 1978). Vertical variations of these authigenic mineral phases in the Naivasha sediment sequence thus define lake-level fluctuations and alkalinity changes through time. Freshwater phases are characterized by diatomite, unaltered volcanic glass, and absence of authigenic silicates. In contrast, silicic glass with perlitic cracks, glass shards with montmorillonite rims, occasional chabazite, and phillipsite represent the transition to alkaline conditions with a pH of ~9. Even higher alkalinity resulted in the formation of clinoptilolite, and the most alkaline pore waters led to the precipitation of analcime.

RESULTS

Five lake-level highstands and intermittent lowstands can be distinguished in the profile, above silicic lava dated as 320 ± 20 ka and ca. 400 ka deposits of Longonot volcano (Scott, 1980; Clarke et al., 1990), which formed the southern boundary of the Naivasha basin. The first manifestation of a larger lake (highstand V) in this basin is indicated by 145 ± 2 ka fluvial deposits that grade into a 3.3-m-thick diatomite bed. A tuff within this diatomite yields an age of 140 ± 3 ka. Predominant diatom taxa as *Aulacoseira granulata* and *A. goetzeana* suggest a large lake with pH < 8. A lake-level drop is indicated in the upper part of the diatomite bed by superseding fluvial deposits, rare sponge spicules, phytoliths (*Cyperaceae*), and diatom fragments, which are topped by a 112 ± 2 ka tuff. The inference of a major drop in lake level coupled with increasing alkalinity is substantiated by the presence of corresponding authigenic silicates. This lowstand is superseded by highstand IV, indicated by the deposition of a prominent 1.6-m-thick laminated diatomite bed. Diatom species such as *Gomphonema angustatum* and *G. gracile* indicate a large, but shallow freshwater lake. The diatomite bed is overlain by several beds of unaltered pyroclastic material, 107 ± 7 ka, reflecting sustained freshwater conditions. However, in the upper part of this unit, perlitic cracks in glass shards, abundant phytoliths, and erosional unconformities herald a major lake regression and a return to more alkaline conditions. Subaerial conditions appear to have been attained at least along the southern periphery of the basin before an ignimbrite dated as 106 ± 4 ka covered this unit. Waterlaid and partly reworked pyroclastic deposits containing volcanic glass shards with perlitic cracks and montmorillonite rims indicate deposition in a freshwater lake with a pH between 8 and 9, equated with lake-level highstand III. The age of this highstand is defined by three intercalated and relatively unaltered tuffs dated as 92 ± 3, 90 ± 2, and 88 ± 4 ka. A subsequent lake-level lowstand and short periods of intervening subaerial conditions are indicated by mud cracks and impact marks of air-fall pumice lapilli in overlying strata, 91 ± 5 ka. Toward the top, three diatomite beds, to 16 cm thick and intercalated by 80 ± 4 ka pyroclastic material, document highstand II. The diatom assemblages are characterized by *Fragilaria construens*, *F. brevistriata*, and *F. pinnata*, reflecting shallow freshwater conditions, but with a possible connection to a deeper lake in the north. However, the occurrence of *Thalassiosira faurii*, *Mastogloia smithi*, *M. elliptica*, and *Anomoenoneis sphaerophora* contrasts with the older diatomites, suggesting slightly alkaline conditions with a pH just above 8. The deposits of highstand II are overlain by several waterlaid tuff layers, dated as 73 ± 3 and 72.8 ± 1.8 ka, that contain various amounts of zeolites indicating higher alkalinity and lower lake levels. A return to prevailing freshwater conditions is documented by a succession of waterlaid pyroclastic deposits containing unaltered glass shards, indicating a pH < 9. These units are interpreted to correspond to highstand I. Overlying gray air-fall tuffs indicate subsequent subaerial conditions at 59 ± 4 ka. An increasing yellow coloration toward the top and smaller amounts of analcime in the highest parts of these strata as well as in the overlying lake beds and 60 ± 2 ka yellow tuffs suggest a final short lake transgression characterized by high alkalinity before the lake disappeared.

DISCUSSION AND CONCLUSIONS

Because the Naivasha basin was not affected by important tectonic movements or volcanic activity after volcanic closure of the basin ca. 320 ka (Clarke et al., 1990; Strecker et al., 1990), the water-level fluctuations recorded in the Ol Njorowa Gorge sediments (Fig.

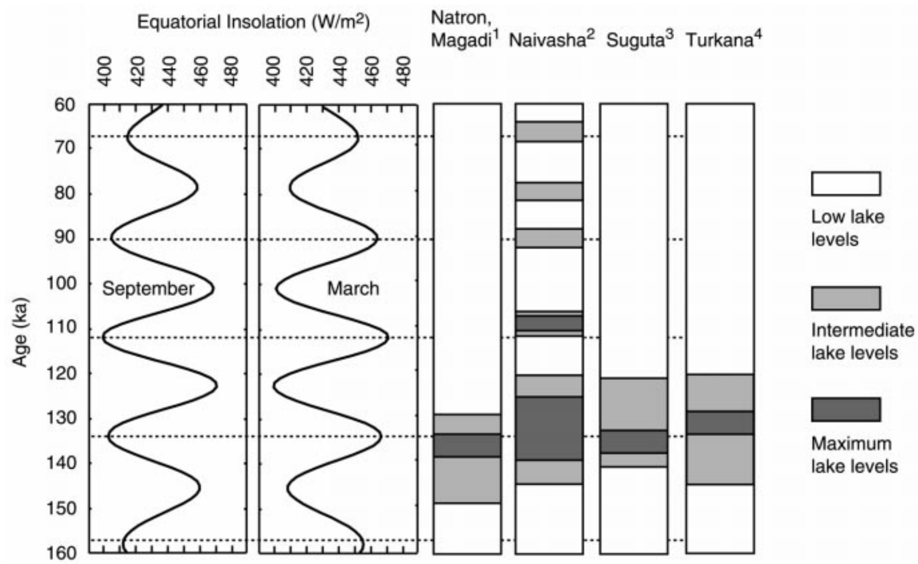

Figure 3. Correlation of East African high lake levels and equatorial insolation changes during late Pleistocene. Data sources: (1) Hillaire-Marcel et al. (1986), (2) this work, (3) Sturchio et al. (1993), (4) Butzer et al. (1969). Insolation data are from Berger (1978).

3) clearly reflect changes in the precipitation and evaporation balance. The first highstand of Lake Naivasha, between 145 and 120 ka with a maximum ca. 135 ka, correlates with highstands in other rift-valley lakes between 140 and 120 ka, such as paleo–Lake Suguta (Sturchio et al., 1993), 135 ka high shorelines in the Magadi-Natron basin (Hillaire-Marcel et al., 1986), and a highstand of Lake Turkana (Butzer et al., 1969). However, paleoecologic information and age control of associated deposits are rather limited. The younger periods of increased humidity at ca. 110, 90, 80 and 66 ka as recorded in the Naivasha sediments have not been reported from other East African lake basins. There is no evidence for higher lake levels between 66 ka and a Holocene highstand of Lake Naivasha between ca. 10 and 9 ka (Washbourn-Kamau, 1977; Richardson and Richardson, 1972).

High lake levels at 135, 110, 90, and ca. 66 ka precisely match maximum spring insolation at the equator without any significant lag (Berger, 1978). The magnitude of the highstands correlates with the amplitude of insolation curve. This suggests that orbitally induced changes in summer solar radiation certainly account for a large part of hydrological changes in East Africa. Such radiation changes could cause a relatively large increase in spring temperatures over land and therefore an intensification of the intertropical convergence and convective rainfall in this region. The long duration of the earliest wet period between 145 and 120 ka as well as a lake-level highstand ca. 80 ka may have been caused by interference between the weakening April–May rains and more intense October–November rains controlled by variations in equatorial insolation during fall.

Summarizing the first continous and precisely dated East African climate record for the last interglacial and the first half of the last glacial, the observed correlation of water-level fluctuations and insolation changes appears compatible with orbital forcing theory (Berger, 1978). As predicted by orbital precession geometry, East African humidity significantly increased ~8 k.y. before the onset of the African-Asian monsoon system as reported from marine records (e.g., Rossignol-Strick, 1983; Clemens and Prell, 1990; deMenocal et al., 1993). The most relevant continental record for North African climate from Lake Abhé in northern Ethiopia (Gasse, 1977) only extends back to ca. 70 ka, and there is good age control only back to ca. 40 ka. The Pretoria Saltpan time series of summer precipitation in South Africa covers the past 200 k.y. (Partridge et al., 1997), but provides radiocarbon ages only back to ca. 43 ka. The lower part of that record was tuned using a fission-track age for the formation of the Saltpan basin of ca. 220 ± 52 ka. Both records are therefore difficult to use for a correlation with the Naivasha record.

There are still large gaps in climate information for Africa for the time before the last glacial maximum. Taking into account the reported inconsistencies in the timing of hydrological changes explained by radiation changes, fluctuations in sea-surface conditions, and ocean-atmosphere interactions, further long high-resolution climate studies are needed for elucidating large-scale atmospheric dynamics during the last two glacial-interglacial cycles. Such results would provide important constraints for future modeling and prediction of African climatic conditions and hydrological budgets.

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