Paleoenvironmental interpretation of lake-margin deposits using $\delta^{13}C$ and $\delta^{18}O$ results from early Pleistocene carbonate rhizoliths, Olduvai Gorge, Tanzania

Cynthia M. Liutkus*
James D. Wright
Gail M. Ashley
Department of Geological Sciences, Rutgers University, 610 Taylor Road, Piscataway, New Jersey 08854, USA
Nancy E. Sikes* Human Origins Program, National Museum of Natural History, Smithsonian Institution, Washington, D.C. 20560, USA

ABSTRACT

Isotope analyses of lake-margin rhizoliths from paleo–Lake Olduvai (ca. 1.75 Ma) form the basis of a new model proposed here for interpreting stable isotope values of phreatic rhizolith carbonates. Average $\delta^{18}O$ and $\delta^{13}C$ values from rhizoliths formed in transgressive lacustrine (waxy) claystones are relatively low. Low $\delta^{18}O$ averages (−5.5‰) reflect meteoric water values consistent with increased precipitation during wet periods that would increase the outflow of fresh water from subsurface seeps and shift a brackish groundwater zone lakeward. Low $\delta^{13}C$ averages (−4.1‰) could indicate little atmospheric exchange, high plant decay, and/or increased groundwater (low $\delta^{13}C$) flow. Higher averages in $\delta^{18}O$ (−3.6‰) and $\delta^{13}C$ (−2.0‰) occur during dry periods and lake regressions (earthy claystones), when hydraulic head is reduced, the lake recedes, and water within the wetlands is subjected to intense evaporation and gas exchange with the atmosphere. The isotope ratios of the rhizoliths from lowermost Bed II change in response to groundwater hydrology on Milankovitch time scales, but the isotopes also provide evidence of shorter-term (decadal to centennial scale) climate fluctuations. The orbitally driven climate changes are recorded faithfully by lithologic variations and stable isotope patterns.

Keywords: Olduvai Gorge, rhizolith, oxygen isotope, carbon isotope, paleoclimate.

INTRODUCTION

Olduvai Gorge, Tanzania, having long captured interest with its rich anthropological record (Leakey, 1971), also contains a 2 m.y. record of terrestrial climate change (Hay, 1976). Cerling and Hay (1986) used the $\delta^{13}C$ and $\delta^{18}O$ changes in carbonate to reconstruct regional paleoenvironmental changes for the Pliocene–Pleistocene. Their work concluded that the regional climate became more arid and that the proportion of C_4 plants (mainly tropical grasses) increased over the past 2 m.y. Although Hay's (1976) paleoenvironmental reconstructions also showed a long-term progression to more arid conditions over the past 2 m.y., Ashley and Driese (2000) and Ashley and Hay (2002) examined high-resolution lower Pleistocene sedimentary records from Olduvai Gorge, focusing their work on lowermost Bed II. Their work suggests that lake cycles were most likely driven by precession and obliquity cycles (Ashley and Driese, 2000).

In this study we generate stable isotope data from carbonate rhizoliths collected from both transgressive and regressive phases of lake-margin deposits of paleo–Lake Olduvai to determine if stable isotope values record changing environmental conditions. We chose lowermost Bed II at Olduvai Gorge because the stratigraphy and depositional environments are well established (Hay, 1976; Ashley and Hay, 2002) and the age is reasonably well constrained (1.79–1.74 Ma; Walter et al., 1991; Hay and Kyser, 2001). We analyzed rhizoliths because they are common in the lake-margin sediments and their origin is considered to be nearly contemporaneous with sediment deposition. Set in a closed basin, the saline alkaline paleo–Lake Olduvai would have been sensitive to hydrologic variations.

GEOLOGIC AND DEPOSITIONAL SETTINGS

Olduvai Gorge is incised into the eastern margin of the Serengeti Plain at ~3°S in Tanzania, East Africa (Fig. 1). Walls of the gorge expose a 100-m-thick Pliocene–Pleistocene record of interbedded tuffs and reworked volcaniclastic sedimentary rocks containing a rich vertebrate and cultural record (Leakey, 1971). Olduvai developed as a small sedimentary basin on the platform margin of the Gregory rift (Ashley and Hay, 2002). The enclosed basin (~40 km wide) had a central playa lake that expanded and contracted with climatic changes. A groundwater discharge zone (seeps and springs) developed at the base of the highlands on the southeast margin of the lake, supporting a large (3 km^2) fresh water wetland (Ashley, 1996; Liutkus and Ashley, 2003). The adjacent lake often flooded the wetland during periods of increased precipitation and contracted during drier episodes.

The deposits of the fluctuating saline alkaline paleolake are green waxy claystones rich in Mg-smectite (Hay, 1976). In contrast, the deposits of the fresh water wetlands are more earthy, and have clays similar to the lake clays, but mixed with biogenic silica, eolian detritus, and indicators of freshwater such as sponges and aquatic plant fragments (Hay, 1976; Ashley, 1996; Liutkus and Ashley, 2003). The rhizoliths are cylindrical, sediment- and/or cement-filled casts of roots of variable length (1–8 cm or longer) and width (~0.2–1.5 cm) found in both the earthy and waxy units (Klappa, 1980). Rhizoliths found in earthy claystones are vertical, while orientation in waxy claystones varies.

STABLE ISOTOPE ANALYSIS

Methods

We selected 25 carbonate rhizoliths from 11 different locations representing an ~1.25 km^2 area within the wetlands region of lowermost Bed II (Fig. 1). We avoided any rhizoliths that displayed white or chalky rims or sparry calcite (Mount and Cohen, 1984). Samples of carbonate were taken at ~0.5 mm intervals across each rhizolith by using a drill with a 0.5 mm drill bit (Fig. 2A) and then analyzed at the Stable Isotope Laboratory at Rutgers University on a Micromass Optima Mass Spectrometer with an attached Multi-Prep device. The 154 samples were reacted in 100% phosphoric acid at 90 °C for 13 min. The $\delta^{13}C$ and $\delta^{18}O$ values are reported relative to the Vienna Peedee belemnite (VPDB) isotope standard through analysis of NBS-19, which yielded values of 1.95‰ and −2.2‰ for $\delta^{13}C$ and $\delta^{18}O$, respectively (Coplen et al., 1983; Appendix Table DR1[1]).

*Present addresses: Liutkus—Department of Geology, Bucknell University, Lewisburg, Pennsylvania 17837, USA; Sikes—SWCA Environmental Consultants, 23392 Madero, Suite L, Mission Viejo, California 92691, USA.

[1]GSA Data Repository item 2005069, Olduvai rhizolith isotope data, is available online at www.geosociety.org/pubs/ft20050.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

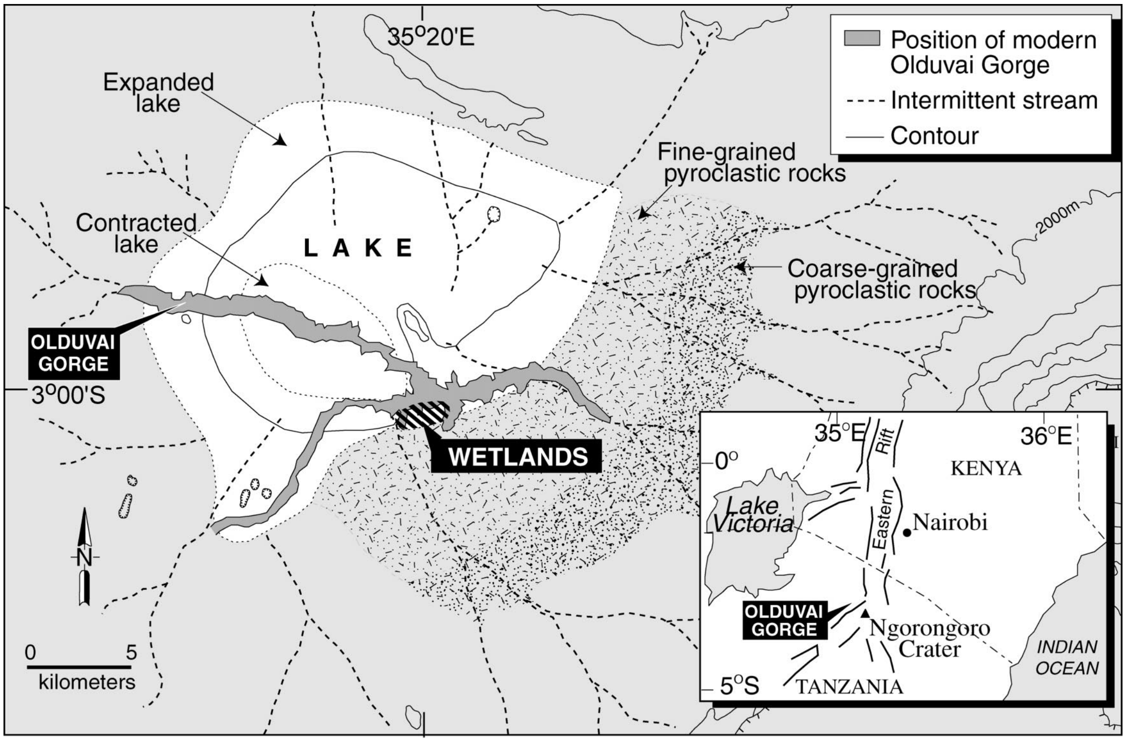

Figure 1. Map showing paleolandscape reconstruction of Olduvai Gorge region of East Africa during Pleistocene (modified from Hay, 1976). Wetlands region is small area restricted to southeastern part of lake margin. Inset map shows location of Olduvai Gorge on western margin of Gregory rift in northern Tanzania, lat ~3°S (modified from Sutcliffe, 1985).

Results

In 21 of the 25 micritic rhizoliths, $\delta^{13}C$ and $\delta^{18}O$ values vary systematically in coherent patterns across individual transects. Rhizolith $\delta^{13}C$ and $\delta^{18}O$ values either increased or decreased from the edges to the center, creating a mirror image pattern converging in the middle (e.g., Fig. 2B). This indicates sequential deposition of calcite from rim to center. Additional transects of individual rhizoliths replicated results from the first transects in both absolute values and pattern of variation. Also, the $\delta^{13}C$ and $\delta^{18}O$ values of individual rhizoliths display a strong covariance (Fig. 2C), although the slopes and intercepts vary among the rhizolith population (r^2 values range up to 0.95). The preceding observations give us confidence that the stable isotope values reflect fundamental processes controlling the precipitation of rhizolith calcite in a phreatic setting.

We compare the $\delta^{13}C$ and $\delta^{18}O$ values of lake-margin rhizoliths to their host lithologies to evaluate if a relationship exists (Fig. 3). Rhizoliths from waxy claystone units record lower $\delta^{13}C$ and $\delta^{18}O$ values (mean values = −4.1‰, −5.5‰, for $\delta^{13}C$ and $\delta^{18}O$, respectively) relative to their earthy claystone counterparts (mean values = −2.0‰, −3.6‰, for $\delta^{13}C$ and $\delta^{18}O$, respectively). Within the data set, $\delta^{18}O$ values in the waxy claystone rhizoliths cluster more tightly (1σ = 0.4‰) than those from the earthy claystone rhizoliths (1σ = 0.6‰). Carbon isotope variability is greater in both the waxy and earthy claystone rhizoliths, recording 1σ variations of 1.0‰ and 0.9‰, respectively. The correlation coefficient for covariance between $\delta^{13}C$ and $\delta^{18}O$ values for all of the earthy rhizolith data is 0.76 and for waxy rhizoliths is 0.33.

DISCUSSION

Formation Processes

Precipitation of rhizoliths in the groundwater discharge zone may be understood by examining the processes at work in modern Lake Turkana. Like paleo–Lake Olduvai, Turkana is moderately saline and alkaline. The modern lake has a relatively low concentration of Ca^{2+}, but only slight changes in lake chemistry are sufficient to precipitate calcite (Halfman et al., 1989). The Omo River provides ~90% of the freshwater flowing into the lake, and its volume varies with rainfall in the Ethiopian highlands. High discharge dilutes the lake, but supplies Ca^{2+} that is critical to the precipitation of calcite (Halfman and Johnson, 1988). Similarly, the inflow of groundwater to paleo–Lake Olduvai was a likely source for the Ca^{2+} necessary for rhizolith precipitation.

Calcite encrustations (root molds) begin to form around dying or newly dead plant stems and roots (Klappa, 1980; Semeniuk and Meagher, 1981; Cohen, 1982). These carbonate crusts remain open when the plant decays away, and the resulting tubule eventually infills with carbonate to form a solid cast. Carbonate precipitation can occur while the tubule is entirely submerged in water. Ongoing modern studies of phreatic rhizoliths (conducted by Liutkus) suggest rhizolith formation on annual to decadal time scales and confirm the process of subaqueous calcite encrustation.

Variations in $\delta^{13}C$ and $\delta^{18}O$ values may represent a long-term average (10^2–10^4 yr) or a geologically instantaneous event (~1 yr). Therefore, it is important to understand formation rates for rhizoliths in order to use them as paleoclimate recorders. All except four of the lowermost Bed II rhizoliths showed a coherent pattern from the edges toward the middle, indicating continuous calcite precipitation, and rhizoliths from both lithologies showed a range in both $\delta^{13}C$ and $\delta^{18}O$ (see Fig. 2B). Modern saline alkaline lakes expand and contract on annual as well as decadal time scales (e.g., El Niño influences), and this timing suggests that most of the individual rhizoliths calcified on similar time scales. Therefore, interpretation of regional climate variability based on rhizolith $\delta^{13}C$ and $\delta^{18}O$ values must rely on comparing populations, not individual rhizoliths. In other words, when plotting the isotopic data from a large population of rhizoliths, the trends that emerge are explained by regional climate fluctuations (wetting and drying), whereas the isotopic data from individual rhizoliths are better explained by shorter-term environmental changes (sub-Milankovitch climate variability).

Modern data are used to estimate the stable isotope values of the paleolake and wetland waters to provide a baseline for interpreting the rhizolith stable isotope variations. Water temperatures in modern regional freshwater marshes range from 20 to 28 °C (Deocampo, 2001), and modern regional rainfall has an average $\delta^{18}O$ (relative to Vienna standard mean ocean water [VSMOW]) value of −4.0‰ (Cerling and Quade, 1993). Calcite precipitated under these conditions will have $\delta^{18}O$ (VPDB) values of ~−6‰. Cerling et al. (1988) reported that $\delta^{13}C$ values of dissolved inorganic carbon (DIC) in east African rivers

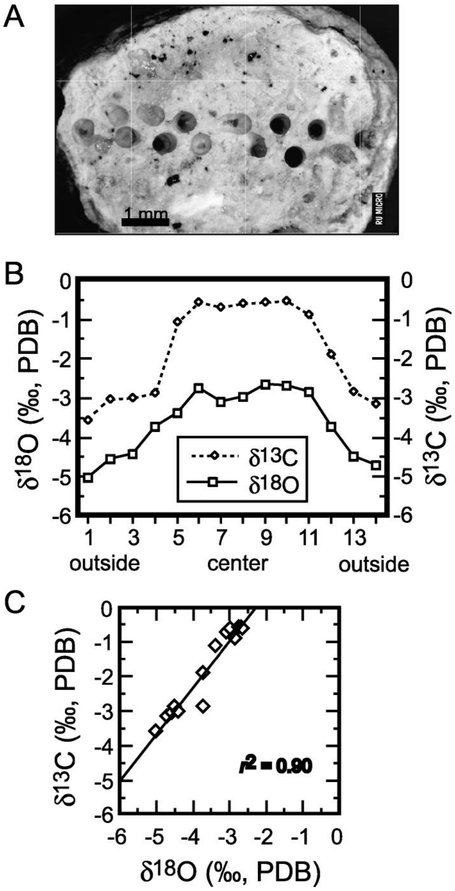

Figure 2. A: Image of Olduvai earthy claystone rhizolith looking down long axis. Small sparry grains are apparent (e.g., between first two holes from left). Drill holes show location of samples across rhizolith. B: $\delta^{13}C$ and $\delta^{18}O$ values plotted vs. location within rhizolith. Numbers on *x*-axis correspond directly with sample holes in A. PDB—Peedee belemnite. C: Plot of data from same sample, $\delta^{13}C$ vs. $\delta^{18}O$. Linear relationship between two isotopes indicates strong covariance (r^2 = 0.90).

vary between −4‰ and −16‰ (VPDB) with an average and mode at −10‰. Calcium carbonate precipitated from water with a DIC $\delta^{13}C$ value of −10‰ would have a $\delta^{13}C$ value of −8‰. DIC $\delta^{13}C$ values for modern east African lakes are significantly higher (−3‰ to +6‰) because of evaporative isotopic exchange with atmospheric CO_2 and/or photosynthesis (Cerling et al., 1988).

Isotopes at Olduvai: Implications for Climate

Oxygen Isotopes. Building on Hay (1976), Ashley and Driese (2000) interpreted the alternating layers of waxy and earthy claystones found in the lowermost Bed II lake margin as representing wet and dry periods, respectively, that were the result of astronomically driven Milankovitch obliquity and precession cycles (40 and ~21 k.y., respectively). Variations in $\delta^{18}O$ values of carbonate result from water $\delta^{18}O$ (determined by evaporation and precipitation ratios) as well as temperature changes (e.g., Li and Ku, 1997; Benson et al., 1996). The equatorial position of the Olduvai basin makes large temperature fluctuations unlikely. Waxy claystone rhizoliths have comparatively low $\delta^{18}O$ values (−7‰ to −5‰), indicating there was a constant supply of fresh water during calcite precipitation (Fig. 3). We envision that during wet periods, the lake-margin region was dominated by increased surface and subsurface flow of fresh water, even though saline alkaline waters filled the lake basin (Hay, 1976) (Fig. 4A). Higher rainfall likely increased groundwater discharge into the lake margin through forced convective flow (Fan et al., 1996), thus shifting a fresh to brackish groundwater zone beneath the lake margin lakeward and freshening the lake margin (Fig. 4A).

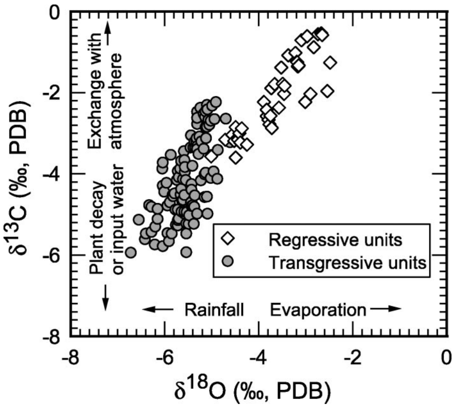

Figure 3. Stable isotope data from individual spot analyses of Olduvai lowermost Bed II rhizoliths, separated by lithology. $\delta^{13}C$ and $\delta^{18}O$ values of rhizoliths from waxy claystones (= transgressive units) are lower than those from earthy claystones (= regressive units). Hypothesized model for interpreting increase or decrease in $\delta^{13}C$ and $\delta^{18}O$ values is superimposed on graph. PDB—Peedee belemnite.

In contrast, rhizoliths from earthy claystones recorded higher $\delta^{18}O$ values (−5‰ to −2‰) (Fig. 3). Precipitation of rhizoliths in these units occurred as the lake regressed under arid conditions and the wetland emerged, groundwater discharge slowed, and the resi-

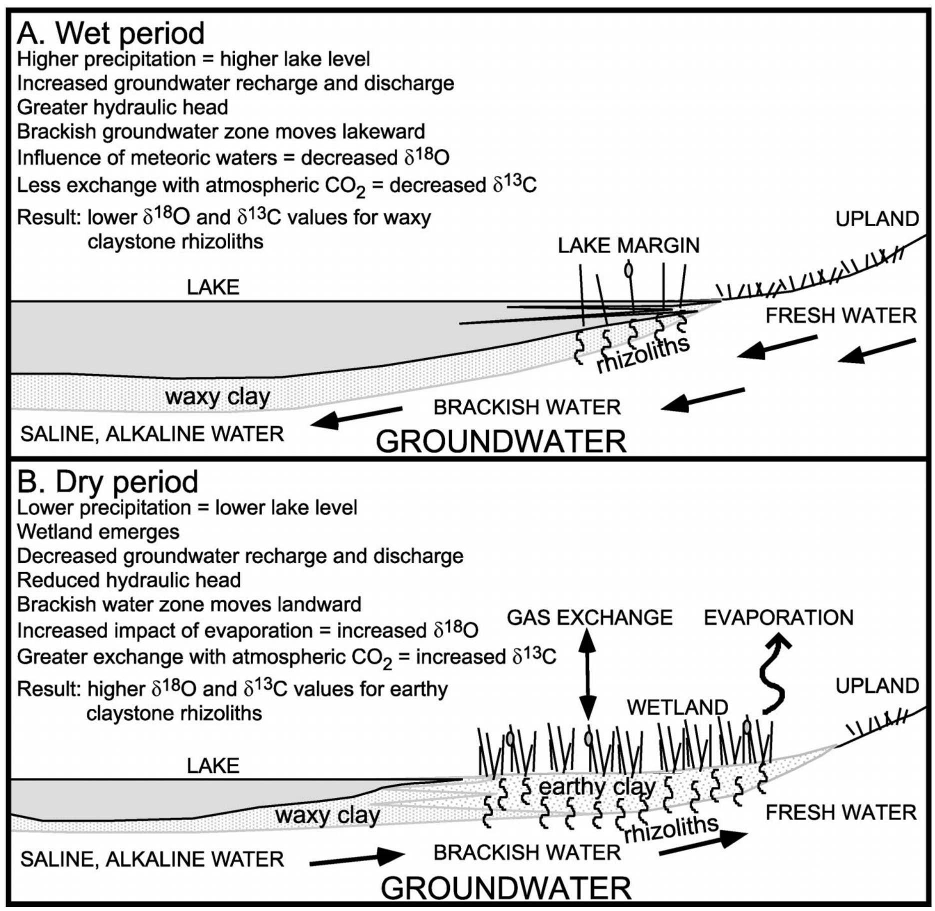

Figure 4. Reconstruction of hydrology of wetlands and lake-margin region of paleo–Lake Olduvai during different climatic regimes in Pleistocene. A: During wet periods, increase in hydraulic head in highlands increases outflow of fresh water into lake margin, resulting in decrease in $\delta^{13}C$ and $\delta^{18}O$ values of waxy claystone rhizoliths due to influence of meteoric waters and reduced exchange with atmospheric CO_2, respectively. B: During drier periods, paleolake recedes, and water in emergent wetland is subject to evaporation and exchange with atmospheric CO_2, resulting in increase in $\delta^{13}C$ and $\delta^{18}O$ values of earthy claystone rhizoliths.

dence time of water in the wetlands increased (Fig. 4B). Free convective flow shifted the saline to brackish groundwater zone landward, allowing more saline waters to saturate the lake-margin subsurface (Fan et al., 1996). Residence times increased with reduced hydraulic head, allowing time for evaporative concentration to drive the $\delta^{18}O$ values of the waters in the wetland higher. The vertical orientation of earthy claystone rhizoliths supports our interpretation of formation during drier climatic periods when plant roots extend downward to tap groundwater (Mount and Cohen, 1984).

Carbon Isotopes. The $\delta^{13}C$ values of waxy claystone rhizoliths ($-6‰$ to $-2‰$) show an $\sim 4‰$ variability, and the mean $\delta^{13}C$ value of waxy claystone rhizoliths is 2‰ lower than the average for earthy claystone rhizoliths (Fig. 3). Two effects are considered to explain the carbon isotope changes. First, isotopic exchange between water and the atmosphere increases $\delta^{13}C$ values of the water and DIC (Broecker and Peng, 1982; Talbot, 1990). This exchange is further enhanced during evaporation because the total CO_2 concentrations in the water increase. The $\delta^{13}C$ values will continue to increase until isotopic equilibrium is achieved. Second, photosynthesis and plant decay in lake or groundwater sources will increase and decrease lacustrine DIC $\delta^{13}C$ values, respectively (Benson et al., 1996).

Because waxy claystone rhizolith $\delta^{18}O$ values indicate little evaporative concentration, we suggest that photosynthesis and respiration account for much of the $\delta^{13}C$ variability during the wet phase rather than isotopic equilibration between the waters and the atmosphere. In contrast, longer residence time of water in the wetlands led to an increase in the evaporation/precipitation ratio during drier periods. As the lake margin desiccated, isotopic exchange between the wetland water and atmospheric CO_2 pulled DIC $\delta^{13}C$ values higher, causing an increase in $\delta^{13}C$ values of rhizoliths from earthy claystones ($-4‰$ to 0‰). Some photosynthetic activity may have contributed to higher $\delta^{13}C$ values; however, the harsh evaporative conditions were probably not conducive to phytoplankton blooms.

CONCLUSIONS

High-resolution isotope sampling of lake-margin calcite rhizoliths shows that wet-dry cycles are recorded by $\delta^{13}C$ and $\delta^{18}O$ values. The proposed model for interpreting the rhizolith isotope record in lowermost Bed II at Olduvai suggests that during wetter periods, lower $\delta^{18}O$ values reflect increased groundwater discharge, hence reflecting meteoric values, and lower $\delta^{13}C$ values reflect high plant decay and little to no exchange of lake-margin waters and DIC with atmospheric CO_2. During drier periods, the strong influences of evaporation and CO_2 exchange, coupled with reduced discharge and high productivity, drive $\delta^{13}C$ and $\delta^{18}O$ values higher. Owing to the relationship between evaporation and inflow, $\delta^{13}C$ and $\delta^{18}O$ values of phreatic rhizoliths covary. We propose that short-term climatic changes (years to decades) within longer Milankovitch-scale climate variations are ultimately responsible for the isotope values recorded by individual lake-margin rhizoliths. The overall lithologic and stable isotope variations are the result of changes in the East Africa monsoon system. Insolation patterns that affect land-sea temperature differences directly control mean precipitation delivered to East Africa (Trauth et al., 2001). These orbitally driven climate changes are recorded faithfully by lithologic variations and phreatic rhizolith stable isotope patterns.

ACKNOWLEDGMENTS

This research was supported in part by National Science Foundation grants to R.J. Blumenschine and F.T. Masao (SBR-9602478, SBR-961065, BNS-9000099), G.M. Ashley and J.S. Delaney (GEO-9903258), and N.E. Sikes (SBR-9805846) as well as a Geological Society of America grant to C.M. Liutkus (1999). Grants awarded to Sikes by the following foundations also supported this research: L.S.B. Leakey Foundation, Boise Fund, Human Origins and Scholarly Studies Programs, and the Smithsonian Institution. The ideas presented here have evolved from discussions with Richard Hay, Thure Cerling, Dan Deocampo, Craig Feibel, Robin Renaut, Jerry Delaney, Carl Swisher III, Jonathan Wynn, and Claudia Mora, and we thank them sincerely.

REFERENCES CITED

Ashley, G.M., 1996, Springs, pools and adjacent wetlands, a newly recognized habitat, lowermost Bed II, Olduvai Gorge: Geological Society of America Abstracts with Programs, v. 28, no. 6, p. 28.

Ashley, G.M., and Driese, S.G., 2000, Paleopedology and paleohydrology of a volcanic paleosol interval: Implications for early Pleistocene stratigraphy and paleoclimate record, Olduvai Gorge: Journal of Sedimentary Research, v. 70, p. 1065–1080.

Ashley, G.M., and Hay, R.L., 2002, Sedimentation patterns in a Plio-Pleistocene volcaniclastic rift-platform basin, Olduvai Gorge, Tanzania, *in* Renaut, R.W., and Ashley, G.M., eds., Sedimentation in continental rifts: SEPM (Society for Sedimentary Geology) Special Publication 73, p. 107–122.

Benson, L., White, L.D., and Rye, R., 1996, Carbonate deposition, Pyramid Lake subbasin, Nevada: 4. Comparison of the stable isotope values of carbonate deposits (tufas) and the Lahontan lake-level record: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 122, p. 45–76.

Broecker, W.S., and Peng, T.-H., 1982, Tracers in the sea: Palisades, New York, Eldigio Press, 690 p.

Cerling, T.E., and Hay, R.L., 1986, An isotopic study of paleosol carbonates from Olduvai Gorge: Quaternary Research, v. 25, p. 63–78.

Cerling, T.E., and Quade, J., 1993, Stable carbon and oxygen isotopes in soil carbonates, *in* Swart, P.K., et al., eds., Climate change in continental isotope records: American Geophysical Union Geophysical Monograph 78, p. 217–239.

Cerling, T.E., Bowman, J.R., and O'Neil, J.R., 1988, An isotopic study of a fluvial-lacustrine sequence: The Plio-Pleistocene Koobi Fora sequence, East Africa: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 63, p. 335–356.

Cohen, A.S., 1982, Paleoenvironments of root casts from the Koobi Fora Formation, Kenya: Journal of Sedimentary Petrology, v. 52, p. 401–414.

Coplen, T.B., Kendall, C., and Hopple, J., 1983, Comparison of stable isotope reference samples: Nature, v. 302, p. 236–238.

Deocampo, D.M., 2001, Geochemistry and sedimentology of modern East African wetlands and a Pleistocene paleo-wetland at Olduvai Gorge, Tanzania [Ph.D. thesis]: New Brunswick, New Jersey, Rutgers University, 155 p.

Fan, Y., Duffy, C.J., and Oliver, D.S., Jr., 1996, Density-driven groundwater flow in closed desert basins: Field investigations and numerical experiments: Journal of Hydrology, v. 196, p. 139–184.

Halfman, J.D., and Johnson, T.C., 1988, High-resolution record of cyclic climatic change during the past 4 k.y. from Lake Turkana, Kenya: Geology, v. 16, p. 496–500.

Halfman, J.D., Johnson, T.C., Showers, W.J., and Lister, G.S., 1989, Authigenic low-Mg calcite in Lake Turkana, Kenya: Journal of African Earth Sciences, v. 8, p. 533–540.

Hay, R.L., 1976, Geology of the Olduvai Gorge: Berkeley, California, University of California Press, 203 p.

Hay, R.L., and Kyser, T.K., 2001, Chemical sedimentology and paleoenvironmental history of Lake Olduvai, a Pliocene lake in northern Tanzania: Geological Society of America Bulletin, v. 113, p. 1505–1521.

Klappa, C.F., 1980, Rhizoliths in terrestrial carbonates: Classification, recognition, genesis and significance: Sedimentology, v. 27, p. 613–629.

Leakey, M.D., 1971, Olduvai Gorge: Excavations in Beds I and II: 1960–1963: Cambridge, UK, Cambridge University Press, 309 p.

Li, H.-C., and Ku, T.-L., 1997, $\delta^{13}C$-$\delta^{18}O$ covariance as a paleohydrological indicator for closed-basin lakes: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 133, p. 69–80.

Liutkus, C.M., and Ashley, G.M., 2003, Facies model of a semiarid freshwater wetland, Olduvai Gorge, Tanzania: Journal of Sedimentary Research., v. 73, p. 691–705.

Mount, J.F., and Cohen, A.S., 1984, Petrology and geochemistry of rhizoliths from Plio-Pleistocene fluvial and marginal lacustrine deposits, East Lake Turkana, Kenya: Journal of Sedimentary Research, v. 54, p. 263–275.

Semeniuk, V., and Meagher, T.D., 1981, Calcrete in Quaternary coastal dunes in southwestern Australia: A capillary-rise phenomenon associated with plants: Journal of Sedimentary Petrology, v. 51, p. 47–68.

Sutcliffe, A.J., 1985, On the track of ice age mammals: Cambridge, Massachusetts, Harvard University Press, 224 p.

Talbot, M.R., 1990, A review of the palaeohydrological interpretation of carbon and oxygen isotope ratios in primary lacustrine carbonates: Chemical Geology, v. 80, p. 261–279.

Trauth, M.H., Deino, A., and Strecker, M.R., 2001, Response of the East African climate to orbital forcing during the last interglacial (130–117 ka) and the early last glacial (117–60 ka): Geology, v. 29, p. 499–502.

Walter, R.C., Manega, P.C., Hay, R.L., Drake, R.E., and Curtis, G.H., 1991, $^{40}Ar/^{39}Ar$ dating of Bed I, Olduvai Gorge, Tanzania: Nature, v. 354, p. 145–149.

Manuscript received 23 August 2004
Revised manuscript received 27 December 2004
Manuscript accepted 1 January 2005

Printed in USA