High-resolution record of cyclic climatic change during the past 4 ka from Lake Turkana, Kenya

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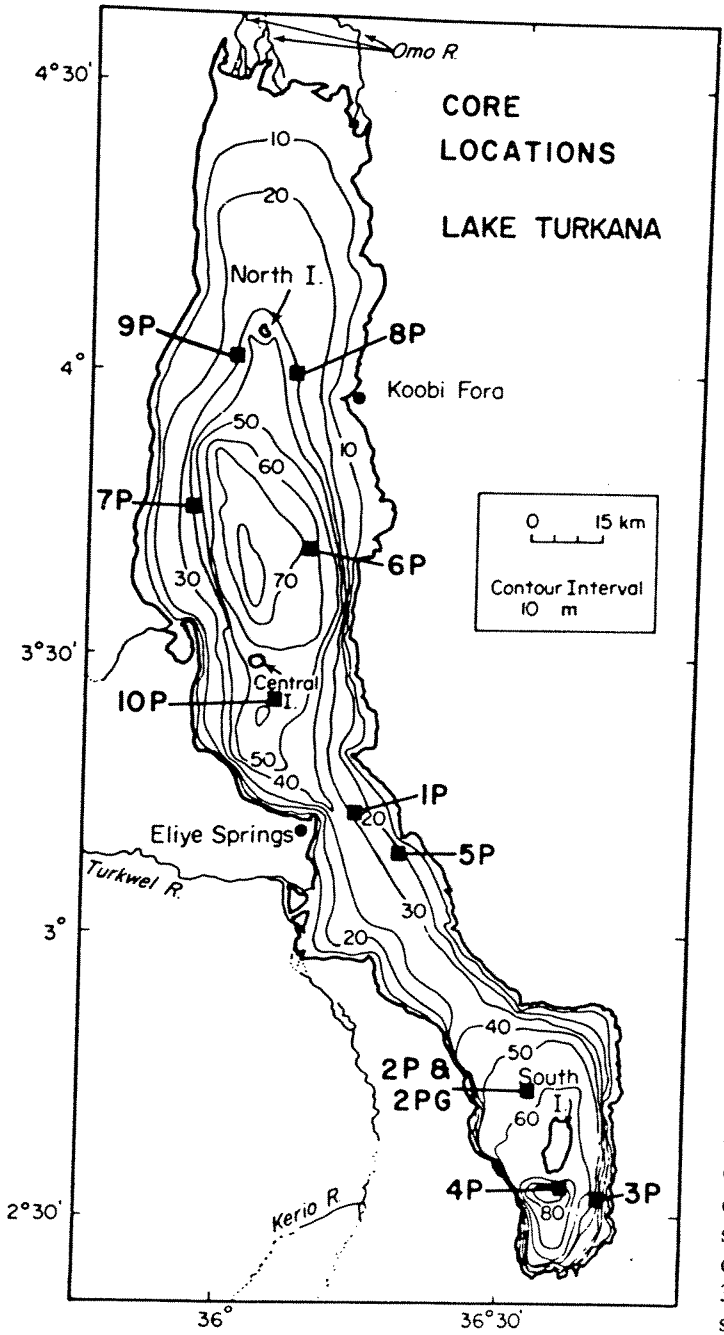

Figure 1. Core locations and bathymetric map of Lake Turkana, Kenya. Core LT84-8P is located 10 km southeast of North Island. North basin extends from Eliye Springs to Omo delta. South basin is approximated by 40 m contour surrounding South Island.

ABSTRACT

Profiles of carbonate content and lamination thickness in an 11.3 m core from Lake Turkana are interpreted as a record of climatic change for the past 4 ka. On a time scale of millennia, the data agree with other paleohydrologic records from sub-Saharan east Africa. Time-series analysis of both data sets reveal periods of about 270, 200, 165, and 100 yr. The thickness data suggest additional periods of about 78, 44, 31, 25, and possibly 20 yr. The sediments consist of laminated light and dark couplets, which are interpreted as a response to an average 4-yr variability in the hydrology of the Ethiopian Plateau. We suggest that this may be a feedback from the El Niño–Southern Oscillation.

INTRODUCTION

Large-scale fluctuations in the level of closed-basin lakes throughout the tropics seem synchronous on a millennial scale for the past 30 ka (Street and Grove, 1979; Street-Perrott and Harrison, 1984). This synchroneity is interpreted to reflect global climatic variability and is predicted by atmospheric general-circulation models and other paleoclimatic records from the tropics (Kutzbach and Street-Perrott, 1985). Here we present the results of sediment analyses of a piston core obtained from Lake Turkana (formerly Lake Rudolf), Kenya, that represents roughly the past 4 ka of lake history. It contains a record of climate change that on a millennial time scale is consistent with previously published data for this region of lowstands from about 2 to 4 ka (see references below). On a shorter time scale, the record reveals climatic cycles of decades to centuries and perhaps the effects of the El Niño–Southern Oscillation.

LAKE TURKANA

Lake Turkana is the largest closed-basin lake in the east African Rift (Fig. 1). It is 250 km long and its mean width is 30 km. The local climate is arid and hot; rainfall is less than 200 mm/yr and an average annual temperature is 30 °C (Ferguson and Harbott, 1982). The lake is moderately saline (2.5‰), alkaline (pH 9.2), and is well mixed by strong, diurnal winds (Yuretich and Cerling, 1983). The Omo River provides about 90% of the water flowing into the basin (Cerling, 1986). It drains southward from the Ethiopian Plateau, where mid-year monsoonal rainfall exceeds 1500 mm.

Lake Turkana responds drastically to climatic variability. Lake level fluctuates approximately 1 m every year, from the seasonal flooding of the Omo River (Ferguson and Harbott, 1982), and has fluctuated over 20 m during the past century (Butzer, 1971). Holocene deposits recording highstands from 50 to 80 m above the present level have been radiocarbon dated from about 10 to 7.5 ka, 6 to 4.2 ka, and, less reliably, from 3.8 to 3.2 ka (Owen et al., 1982). Lowstands at about 60 m below the lake's surface were interpreted from high-resolution seismic profiles and were estimated to have occurred prior to 10 ka (Johnson et al., 1987). The lake level also might be influenced by changes in Omo River drainage (Cerling, 1986) and by tectonically induced change in basin morphology (Rosendahl, 1987).

The profundal sediments of Lake Turkana are primarily silty clays (Yuretich, 1979). The relative abundance of biogenic and authigenic components increases with increasing distance from the Omo River; i.e., from rare and poorly preserved diatom clays in the north basin to well-preserved ostracod-diatom silty clays in the south basin. This trend results from decreased dilution by detrital silicates with increasing distance from the delta (Halfman, 1987). The sediments are laminated, except in the nearshore deposits, despite well-oxygenated bottom waters (Yuretich, 1979; Cohen, 1984). The benthic standing crop, which could potentially homogenize the sediments, consists primarily of epibenthic detritovores (e.g., ostracods). Their abundance declines drastically from nearshore to offshore environments, presumably because of a parallel decline in edible detritus (Cohen, 1984). Yuretich (1979) assumed a seasonal mode of formation for the light and dark couplets related to the seasonal flooding of the Omo River, but he lacked independent age controls to confirm this.

METHODS

We collected 10 piston (Kullenberg) cores, each about 12 m long, from Lake Turkana in November 1984 (Fig. 1). Weight-percent bulk carbonate (CaCO$_3$ wt%) of the dry sediment was determined by a vacuum-gasometric technique (Jones and Kaiters, 1983) in 9 of the 10 cores; an average sample spacing of 35 cm was used. Reproducibility from duplicate measurements was ±0.25 wt%. One of the cores, LT84-8P, was singled out for a detailed, high-resolution analysis that consisted of carbonate analyses with an average sample spacing of 10 cm, and measurement of lamination thickness through the upper 935 cm of the core. Core LT84-8P was selected because (1) the laminations were distinct and the thickness of each light/dark couplet from the bottom of each dark lamination could be measured with the aid of dissecting microscope and computerized digitizer. Reproducibility from duplicate measurements was ±0.1 mm. (2) The initial carbonate profile of core LT84-8P correlated well with the other cores recovered from central and northern Lake Turkana (Halfman, 1987), and was considered a representative record of the lake's upper stratigraphy.

GEOCHRONOLOGY

Five radiocarbon dates were obtained from the bulk carbonate fraction of 10- to 20-cm-thick intervals of core LT84-8P (Beta Analytic #16450-16543, 19457). The dates are reported as radiocarbon years before A.D. 1950 (yr B.P.), using a half-life of 5568 yr, and errors (1 standard deviation) from the counting statistics (Fig. 2). Radiocarbon dating of bulk lacustrine sediment usually results in significant errors in age assignment because of a relatively large and unquantifiable contribution of old, detrital carbon either from the drainage basin or recycled from the sediments. This is not the case in Lake Turkana. The carbonate fraction of the profundal sediments is all authigenic or biogenic (Halfman, 1987; Halfman et al., in prep.), and the lake's high alkalinity promotes rapid equilibration of CO$_2$ with the atmosphere (Peng and Broecker, 1980). There is no significant input of detrital carbonates to Lake Turkana.

A best-fit, linear interpolation of age vs. depth in the core yields an average sedimentation rate of 2.7 mm/yr, and reveals a strong linear trend (correlation coefficient squared, r^2, is 0.96). This sedimentation rate is similar to other estimates (Yuretich, 1979; Ferguson and Harbott, 1982; Yuretich and Cerling, 1983; Halfman, 1987). Our radiocarbon sedimentation rate, in fact, constitutes the most reliable rate available for Lake Turkana. Differences in sedimentation rates that have been observed by the different methods or at different sites can be accounted for by proximity to sediment sources or sediment focusing (Johnson, 1984). The uncertainty associated with the date at the top of the core precludes an accurate assessment for the age of the core top. We suspect that all of the piston cores overpenetrated the lake floor, perhaps by several decimetres, because the uppermost sediments are extremely fluid. We assume the core-top age to be 0 yr, recognizing that this could be off by a few decades. Ages were assigned to the rest of the core on the basis of the linear sedimentation rate of 2.7 mm/yr.

The dates are not corrected for the DeVries, reservoir, or isotopic fractionation effects. The reservoir effect is probably negligible because there is no major source for detrital carbonates, and the core-top sample yielded a nuclear-bomb, enriched C-14 activity; i.e., a post–A.D. 1950 (modern) age. The down-core profile of δ^{13}C is nearly constant (average −0.22‰, standard deviation 0.91 in core LT84-7P). Consequently, isotopic fractionation does not significantly affect the calculated sedimentation rate. If the ages are corrected for the DeVries effect (Klein et al., 1982), the sedimentation rate changes from 2.7 to 2.4 mm/yr.

CARBONATE CONCENTRATION AND THE LONG-TERM RECORD

The carbonate fraction of the sediment consists of ostracod tests and micrite (<44 μm carbonate fraction). The micrite consists primarily of euhedral crystals, about 10 μm in length. Ostracod tests are not common in core LT84-8P; however, samples from core LT84-2P, recovered from the south basin, had abundant ostracods that were compared geochemically to the micrite. The δ^{18}O and δ^{13}C values average 1.4 ±0.26‰ and 0.8 ±0.05‰ (PDB), respectively, in the micrite, and 3.2‰ and −0.7‰ (PDB), respectively, in the ostracods. The isotopic differences and the euhedral nature of the micrite indicate that most of it is not derived from ostracod fragments. The δ^{13}C values of the micrite range from 0.2‰ to 2.0‰. The δ^{13}C values of the dissolved inorganic carbon in the sediment

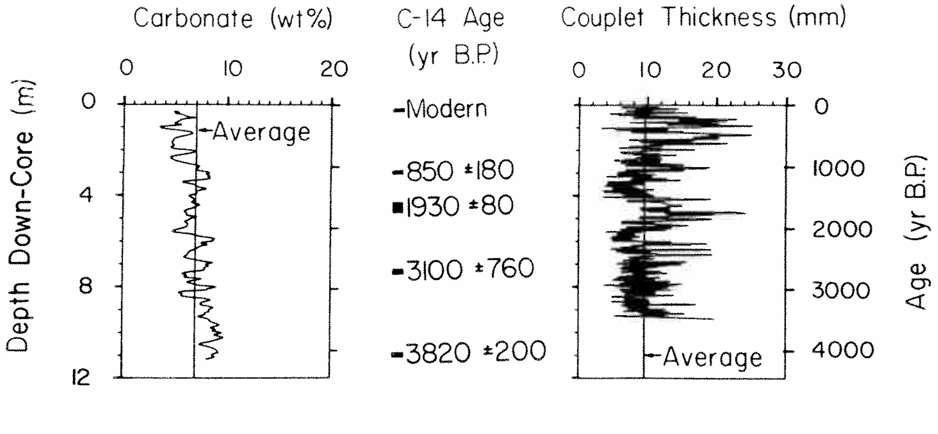

Figure 2. Weight-percent carbonate (CaCO$_3$) of dry sediment and thickness of light-dark couplets vs. depth down-core LT84-8P. Carbonate profile is cubic-spline interpolation through 209 data points. Thickness profile is three-point running average of successive couplet thicknesses. Vertical line represents average value for respective profiles. Radiocarbon dates of carbonate fraction are shown at their respective depths down-core. Linear sedimentation rate of 2.7 mm/yr was used to construct age axis.

pore waters increase from 0‰ at the top of the core to more than 12‰ (PDB) down-core (T. Cerling, 1986, personal commun.). This indicates that the micrite is not a diagenetic precipitate; if it were, the carbon isotope values of the micrite would be heavier (McKenzie, 1985; Talbot and Kelts, 1986). The oxygen isotope values (about 1‰) suggest that the micrite forms authigenically because it is nearly in isotopic equilibrium with the modern lake water (–24.5‰ PDB; Halfman et al., in prep.).

The observed carbonate fluctuation down-core LT84-8P (Fig. 2) could result from past variations in Omo River discharge or biological productivity (Kelts and Hsü, 1978). Higher river discharge will increase the dilution of the biogenic and authigenic carbonates with terrigenous sediment. It also may increase the precipitation of the micrite by supplying dissolved calcium to an alkaline lake. No significant correlation is revealed between the paleoproductivity signal (determined from either weight-percent biogenic silica or weight-percent total organic carbon) and carbonate concentrations from various depths in this and other cores from Lake Turkana (r^2 between 0.05 and 0.3). However, there is a positive correlation between oxygen and carbon isotope values and carbonate concentrations (r^2 between 0.63 and 0.84; Halfman, 1987) for both picked ostracods and micrite samples. The oxygen isotope values in the low-latitude, closed-basin setting are affected mainly by variations in water composition rather than by temperature. During dry periods when the lake is relatively low and saline and the input of isotopically lighter Omo River water is relatively low, the oxygen isotopic composition of the lake water and carbonates would be relatively heavy. We conclude that the long-term variations in the carbonate concentrations in the sediment are influenced primarily by dilution of the carbonates with a variable detrital load dependent on the discharge of the Omo River (i.e., rainfall in Ethiopia).

The carbonate profiles in core LT84-8P and other cores from the north basin indicate a fluctuating lake level about a datum that is inferred to have been at or below the present lake for most of the past 4 ka. Superimposed on the gross trend of increasing carbonate concentrations from the present day to about 4 ka are zones of relatively high carbonate concentrations (inferred low lake levels), which occur from about 1100 to 1500 and 2100 to 4000 yr B.P., on the basis of the geochronology of core LT84-8P. The earlier period correlates to inferred lowstands for Lakes Abhe (Gasse, 1977; Gasse and Street, 1978; Fontes et al., 1985) and Ziway-Shala (Gasse, 1980; Gillespie et al., 1983) in Ethiopia, numerous lakes throughout intertropical Africa (Street-Perrott and Harrison, 1984), and possibly lakes in Rajasthan, India (Swain et al., 1983). Slight differences (about 200 yr) that exist in the exact timing of the lower lake levels as taken from the various records may be due to either local climatic and hydrologic factors or to problems inherent in comparing radiocarbon-dated records. The previously reported highstand for Lake Turkana between 3200 and 3800 yr B.P. is inconsistent with both our results and those of most other works on east African lakes (see references above).

SEDIMENT LAMINATIONS: A POSSIBLE RECORD OF THE EL NIÑO–SOUTHERN OSCILLATION

The sediments in Lake Turkana are faintly laminated with alternating light/dark couplets (Fig. 3). Visual and X-radiograph inspection reveal that the laminae lack graded bedding and are more distinct in the north basin. Neither the light nor the dark layer consistently shows sharper lower contacts; neither has significantly higher biogenic silica, total organic carbon, organic carbon:nitrogen ratio, or coarser grain size. However, the concentration of carbonate is consistently higher in the lighter layers, suggesting that they represent periods of lower Omo River discharge. Each couplet in core LT84-8P represents, on average, a little less than 4 yr on the basis of the average sedimentation rate for the core. If the couplets were annual, then the radiocarbon dates would indicate that 75% of the section is missing; however, there is no independent evidence for hiatuses in the core. For example, there are no erosional lag deposits and no graded beds, and seismic profiles from the core site show a pattern of only simple basin infilling. In addition, a profile of lamination thickness in the upper 3 m of core LT84-9P, recovered from about 15 km west of site LT84-8P and the same distance from the Omo River as LT84-8P, correlates well with the upper 3 m of core LT84-8P (Halfman, 1987). We conclude that the iments are responding to an interannual variability of the Omo

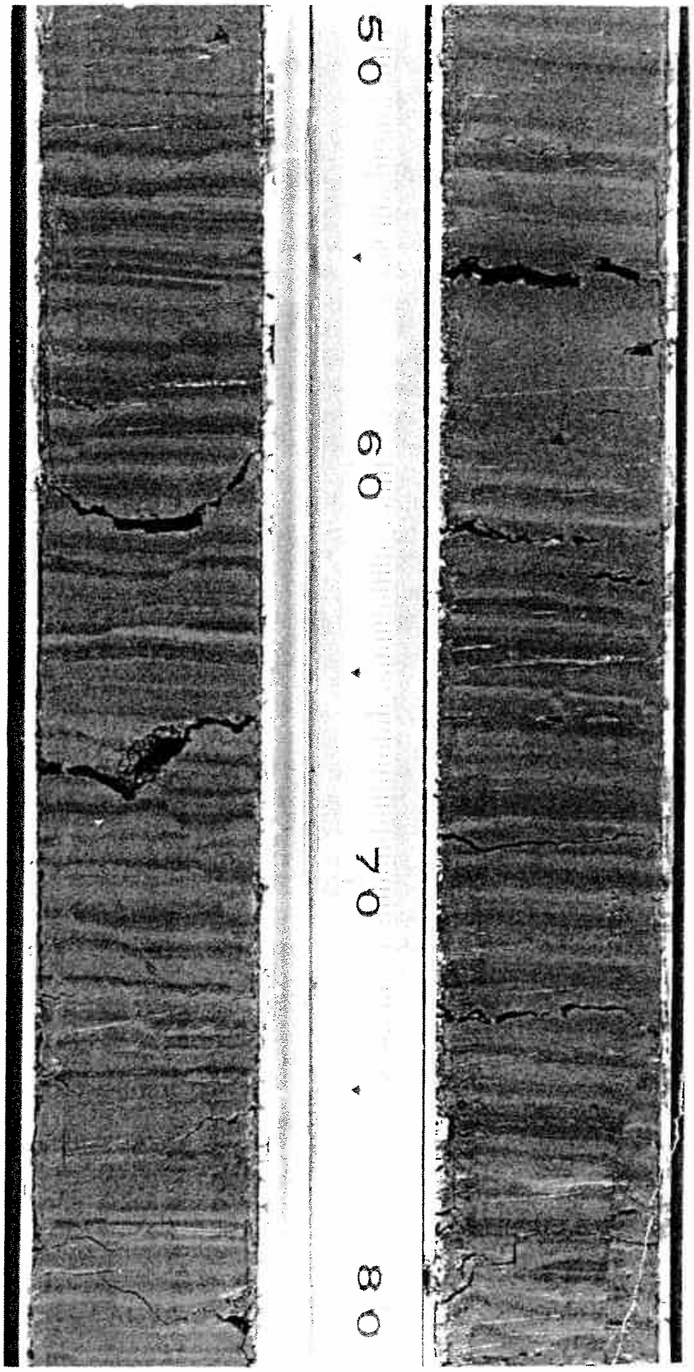

Figure 3. Representative section of core LT84-8P (left: 549 to 582 cm downcore; right: 649 to 682 cm down-core) shows alternating light and dark laminations.

River. An exact 4-yr periodicity is not implied; instead, the recurrence interval may vary, but over a long period it averages about 4 yr.

Omo River discharge data are not available for a direct test of our hypothesis. The El Niño–Southern Oscillation (ENSO) is associated with sea-surface pressure, temperature, regional circulation, and precipitation anomalies throughout the tropics (Rasmusson and Carpenter, 1982). The recurrence interval of ENSO ranges from 2 to 10 yr and averages about 4 yr (Quinn et al., 1978). Yearly precipitation records for Jima and Addis Ababa, Ethiopia, which are located within and just to the northeast of the Omo River headwaters, respectively, reveal that a majority (>73%) of the ENSO years had lower rainfall than both the preceding and following years (Halfman, 1987). Rainfall data from east-central Africa and India averaged over various districts reveal interannual variability on a scale of 2 to 5 yr (Rodhe and Virji, 1976; Campbell et al., 1983). Sahel rainfall negatively correlates with ENSO years (Folland et al., 1986). The impact of ENSO on east African climate, coupled with the coincidence of the temporal frequencies of the Turkana laminations and ENSO, suggests that the light layers in core LT84-8P were formed during ENSO events. All of our piston cores overpenetrated the lake floor by an unknown amount, so we have no direct means of proving this hypothesis by comparison of the uppermost sediment record with the limited historical weather data.

Couplet thickness shows a weak negative correlation to the carbonate content ($r = -0.51$). Depth intervals of relatively low concentrations of carbonate match relatively thicker couplets (e.g., 0.5 to 2.9 m and 4.0 to 5.6 m; Fig. 2). Detailed analyses of 56 successive laminae show that groups of successive laminae containing higher carbonate content generally have thinner couplets and finer grain size (Halfman, 1987). Below 935 cm depth in the core, the laminations are too faint to distinguish. This depth corresponds to a period of high carbonate values, suggesting that lower lake levels or slower sedimentation rates may have allowed more wave activity or bioturbation to disturb the laminations.

We suggest that the light layers coincide with dry years in the Ethiopian Plateau, and perhaps ENSO events. It is surprising that this interannual variability can have a greater impact on sediment appearance and composition than the seasonal cycle. This is the only interpretation compatible with our five reliable radiocarbon dates. It is possible that either severe wave activity associated with the strong diurnal winds on Lake Turkana or the benthic standing crop is capable of reworking surface sediments sufficiently to homogenize the seasonal record, yet leave the interannual record intact.

TIME-SERIES ANALYSIS AND CYCLIC VARIABILITY

Cyclic variability in the fluctuations of the carbonate and lamination-thickness data was tested by a Fast Fourier Transformation (FFT). The two independent data sets were smoothed with a three-point running average prior to FFT analysis. A clamped, cubic-spline routine was used to interpolate a carbonate value for every centimetre down-core. The linear trend of the interpolated carbonate values was removed by the least-squares, linear regression of the data. The FFT yielded harmonics in terms of depth intervals, which were converted to time intervals by using the linear sedimentation rate of 2.7 mm/yr. The linear trend of the smoothed thickness curve was removed in a similar fashion. The FFT yielded harmonics in terms of numbers of lamination couplets. These were converted to time intervals by using the mean couplet thickness and mean sedimentation rate for the core. The chi-square test determined the 95% confidence limit for the resulting power spectra.

Numerous spectral peaks were found to be significant and consistent between the two data sets (Fig. 4). These correspond to periods of about 270 ±20, 200 ±12, 165 ±10, and 100 ±5 yr. The thickness data suggest additional peaks at about 78 ±3, 44 ±2, 31 ±1, and 25 ±1 yr. These shorter periods would not be resolved in the smoothed carbonate curve. The results suggest cyclic variability in the climate of the Ethiopian Plateau and Turkana basin on a time scale of decades to centuries. The error associated with these cycles was estimated by calculating the time span in years between successive harmonics. The resolution for the data sets is not adequate to detect cycles less than approximately 20 yr for the thickness data and 50 yr for the carbonate data on the basis of sample spacing and down-core averaging. The down-core cycles in carbonate content may, in part, reflect noise created by sampling predominately light or dark laminae because successive laminations reveal an average 1% difference in carbonate content. The consistency between the two data sets indicates that the contribution from noise is minimal compared to the climatic forcing.

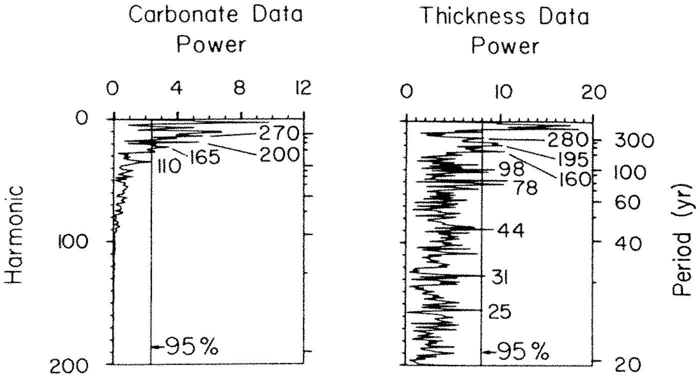

Figure 4. Power spectra from Fast Fourier Transformation of carbonate and thickness data sets. Powers corresponding to harmonics greater than 200 were not plotted because of their limited significance. Vertical line represents 95% confidence limit. Peaks in power spectrum are labeled with corresponding periodicity in years.

The validity of the decade-to-century variability in the paleoclimatology can be tested by analyzing the persistence and correlation of the variability. FFT analysis on three 512-point subsets from the beginning, middle, and end of each data set provided similar spectral features suggesting that the climatic variability has been persistent through the last 4 ka. The cycles observed in the LT84-8P data sets were also found in the preliminary analysis of carbonate profiles from LT84-7P and LT84-10P and in two sections of thickness data (256 couplets each) from LT84-9P. The LT84-9P data sets are too short to statistically reveal periodicities longer than 100 yr; however, they reveal a possible 20-yr periodicity.

Periods longer than 30 yr have been observed in a few other proxy records; i.e., 31 yr in Senegal River discharge records (Faure and Gac, 1981), 45 yr in Holocene Hudson Bay beach ridges (Fairbridge and Hillaire-Marcel, 1977), 77 yr in Nile River flood data (Hameed, 1984), 78 and 181 yr in Camp Century ice core (Johnsen et al., 1970), and 90 and 290 yr in varved Elatina Formation (Williams, 1981). All of these records, however, contain just one or two of the cycles, and most are much shorter than the Turkana sediment record. The periods reported here are rarely detected because there is a dearth of long, continuous records with adequate temporal resolution.

The presence of cycles in the sedimentary record of Lake Turkana is unquestionable. The reported periods, however, may be changed by additional dating or other core analyses. The DeVries effect on radiocarbon dates, for example, would increase all of the periods by about 10%.

Controls for cyclic climate behavior on the Ethiopian Plateau are not known. Climatic variability has been attributed to sunspot cycles and cycles in lunar and other planetary orbital parameters (Fairbridge, 1984). All of the periods reported here can be correlated to one or more planetary cycles. For example, the 44-yr period may correspond to the 44.48-yr

"Double-Hale" solar cycle or the 45.387-yr Uranus-Saturn lap cycle; the 78-yr period may correspond to the 79.4-yr "Gleisburg" cycle; and the 178-yr "King-Hele" solar cycle and the 177.92-yr Sun-Jupiter repeat cycle are within the error range of the 165-yr period reported here. However, correlation of our results to planetary motions is highly speculative at this time and should be viewed only as an intriguing possibility for further study.

REFERENCES CITED

Butzer, K.W., 1971, Recent history of an Ethiopian delta: Chicago, University of Chicago Press, 184 p.

Campbell, W.H., Blechman, J.B., and Bryson, R.A., 1983, Long-period tidal forcing of Indian monsoon rainfall: A hypothesis: Journal of Climate and Applied Meteorology, v. 22, p. 287–296.

Cerling, T.E., 1986, A mass-balance approach to basin sedimentation: Constraints on the recent history of the Turkana Basin: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 43, p. 129–151.

Cohen, A.S., 1984, Effect of zoobenthic standing crop on laminae preservation in tropical lake sediment, Lake Turkana, East Africa: Journal of Paleontology, v. 58, p. 499–510.

Fairbridge, R.W., 1984, Planetary periodicities and terrestrial climate stress, *in* Mörner, N.A., and Karlen, W., eds., Climatic changes on a yearly to millennial basis: Boston, D. Reidel, p. 509–520.

Fairbridge, R.W., and Hillaire-Marcel, C., 1977, An 8,000-yr palaeoclimatic record of the 'Double-Hale' 45-yr solar cycle: Nature, v. 268, p. 413–416.

Faure, H., and Gac, J.Y., 1981, Will the Sahelian drought end in 1985?: Nature, v. 291, p. 475–478.

Ferguson, A.J.D., and Harbott, B.J., 1982, Geographical, physical and chemical aspects of Lake Turkana, *in* Hopson, A.J., ed., Lake Turkana: A report on the findings of the Lake Turkana Project, 1972–1975: London, Overseas Development Administration, p. 1–107.

Folland, C.K., Palmer, T.N., and Parker, D.E., 1986, Sahel rainfall and worldwide sea temperatures, 1901–85: Nature, v. 320, p. 602–607.

Fontes, J.C., Gasse, F., Callot, Y., and Plaziat, J.C., 1985, Freshwater to marine-like environments from Holocene lakes in northern Sahara: Nature, v. 317, p. 608–610.

Gasse, F., 1977, Evolution of Lake Abhe (Ethiopia and TFAI), from 70,000 b.p.: Nature, v. 265, p. 42–45.

—— 1980, Late Quaternary changes in lake levels and diatom assemblages on the southeastern margin of the Sahara: Palaeoecology of Africa, v. 12, p. 333–350.

Gasse, F., and Street, F.A., 1978, Late Quaternary lake-level fluctuations and environments of the northern Rift Valley and Afar region (Ethiopia and Djibouti): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 24, p. 279–325.

Gillespie, R., Street-Perrott, F.A., and Switsur, R., 1983, Post-glacial arid episodes in Ethiopia—Implications for climatic prediction: Nature, v. 306, p. 680–683.

Halfman, J.D., 1987, High-resolution sedimentology and paleoclimatology of Lake Turkana, Kenya [Ph.D. thesis]: Durham, North Carolina, Duke University, 180 p.

Hameed, S., 1984, Fourier analysis of Nile flood levels: Geophysical Research Letters, v. 1, p. 843–845.

Johnsen, S.J., Dansgaard, W., Clausen, W., and Langway, C.C., 1970, Climatic oscillations 1200–2000 AD: Nature, v. 227, p. 482–483.

Johnson, T.C., 1984, Sedimentation in large lakes: Annual Reviews of Earth and Planetary Science, v. 12, p. 179–204.

Johnson, T.C., Halfman, J.D., Rosendahl, B.R., and Lister, G.S., 1987, Climatic and tectonic effects on sedimentation in a rift valley lake: Evidence from Lake Turkana, Kenya: Geological Society of America Bulletin, v. 98, p. 439–447.

Jones, G.A., and Kaiters, P., 1983, A vacuum-gasometric technique for rapid and precise analysis of calcium carbonate in sediments and soils: Journal of Sedimentary Petrology, v. 53, p. 655–660.

Kelts, K., and Hsü, 1978, Freshwater carbonate sedimentation, *in* Lerman, A., ed., Lakes: Geology, chemistry, physics: New York, Springer-Verlag, p. 295–323.

Klein, J., Lerman, J.C., Damon, P.E., and Ralph, E.K., 1982, Calibration of radiocarbon dates: Radiocarbon, v. 24, p. 103–150.

Kutzbach, J.E., and Street-Perrott, F.A., 1985, Milankovitch forcing of fluctuations in the level of tropical lakes from 18 to 0 kyrs BP: Nature, v. 317, p. 130–134.

McKenzie, J.A., 1985, Carbon isotopes and productivity in the lacustrine and marine environment, *in* Stumm, W., ed., Chemical processs in lakes: New York, Wiley, p. 99–118.

Owen, R.B., Barthelme, J.W., Renaut, R.W., and Vincens, A., 1982, Palaeolimno ogy and archaeology of Holocene deposits north-east of Lake Turkana, Keny Nature, v. 298, p. 523–529.

Peng, T., and Broecker, W., 1980, Gas exchange rates for three closed-basin lake Limnology and Oceanography, v. 25, p. 789–796.

Quinn, W.H., Zopf, D.O., Short, K.S., and Kuo Yang, R.T.W., 1978, Historic trends and statistics of the southern oscillation, El Nino, and Indonesia droughts: Fishery Bulletin, v. 76, p. 663–678.

Rasmusson, E.M., and Carpenter, T.H., 1982, Variations in tropical sea surfac temperatures and surface wind fields associated with the Southern Oscillation El Nino: Monthly Weather Review, v. 111, p. 517–528.

Rodhe, H., and Virji, H., 1976, Trends and periodicities in east African rainfall dat Monthly Weather Review, v. 104, p. 307–315.

Rosendahl, B.R., 1987, Architecture of continental rifts with special reference t East Africa: Annual Reviews of Earth and Planetary Science, v. 1 p. 445–503.

Street, F.A., and Grove, A.T., 1979, Global maps of lake level fluctuations sinc 30,000 yr BP: Quaternary Research, v. 12, p. 83–119.

Street-Perrott, F.A., and Harrison, S.P., 1984, Temporal variations in lake level since 30,000 yr B.P.—An index of the global hydrological cycle, *in* Hanse J.E., and Takahashi, T., eds., Climate processes and climate sensitivity: Amer can Geophysical Union Monongraph 29, p. 118–129.

Swain, A.M., Kutzbach, J.E., and Hastenrath, S., 1983, Estimates of Holocen precipitation for Rajasthan, India, based on pollen and lake-level data: Quaternary Research, v. 19, p. 1–17.

Talbot, M.R., and Kelts, K., 1986, Primary and diagenetic carbonates in the anoxi sediments of Lake Bosumtwi, Ghana: Geology, v. 14, p. 912–916.

Williams, G.E., 1981, Sunspot periods in the late Precambrian glacial climate an solar-planetary relations: Nature, v. 291, p. 624–628.

Yuretich, R.F., 1979, Modern sediments and sedimentary processes in Lake Rudol (Lake Turkana), Eastern Rift Valley, Kenya: Sedimentology, v. 2 p. 313–331.

Yuretich, R.F., and Cerling, T.E., 1983, Hydrogeochemistry of Lake Turkan Kenya: Mass balance and mineral reactions in an alkaline lake: Geochimica e Cosmochimica Acta, v. 47, p. 1099–1109.

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Reviewer's comment

Careful, thoughtful analysis of interesting (and somewhat difficult) dat from an important region—important in the past in terms of Holocen (perhaps earlier) human environments; important today because of th sub-Saharan droughts.

Léo Laport