

Sedimentation and recent history of a freshwater wetland in a semi-arid environment: Lobo Swamp, Kenya, East Africa

G. M. ASHLEY*, J. MAITIMA MWORIA†, A. M. MUASYA‡, R. B. OWEN§, S. G. DRIESE¶, V. C. HOVER**, R. W. RENAUT††, M. F. GOMAN‡‡, S. MATHAI§§ and S. H. BLATT¶¶

*Department of Geological Sciences, Rutgers University, Piscataway, NJ 08854-8066, USA (E-mail: gmashley@rci.rutgers.edu)

†International Livestock Research Institute, PO Box 30709, Nairobi, Kenya

‡East African Herbarium, National Museums of Kenya, Nairobi, Kenya

§Department of Geography, Hong Kong Baptist University, Hong Kong, China

¶Department of Geological Sciences, University of Tennessee, Knoxville, TN 37996, USA

**Department of Earth and Environmental Sciences, Rutgers University, Newark, NJ 07102, USA

††Department of Geological Sciences, University of Saskatchewan, Saskatoon, SK, S7N 5E2, Canada

‡‡Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, NY 14853, USA

§§Department of Paleobotany, National Museums of Kenya, Nairobi, Kenya

¶¶Department of Anthropology, Rutgers University, New Brunswick, NJ 08901, USA

ABSTRACT

Lobo Swamp is a 1.5 km² freshwater wetland situated near the equator in the Kenya Rift Valley. The climate is semi-arid: precipitation is ≈ 700 mm year⁻¹, and evapotranspiration is ≈ 2500 mm year⁻¹. Some of the wetland water is currently used for irrigation. An interdisciplinary study was conducted on the geology, hydrology, pedology and biology of the wetland to determine its origin and history and to assess its longevity under present hydrological conditions. Sedimentary records from two piston cores (1.8 and 4 m long) indicate that the present wetland developed during the late Holocene on a low-relief alluvial plain. Floodplain deposits (sandy silts) are capped with wetland sediments (organic-rich clay and peat), which began to form at ≈ 700 BP. The swamp is dominated by *Typha domingensis* Pers. ($\approx 80\%$) and floating *Cyperus papyrus* L. (20%). It is fed by warm springs ($T \approx 35$ °C; pH ≈ 6.4 – 6.9) emanating from grid faults of the rift floor. Water compositions suggest that sources are dominated by shallow meteoric water, with little contribution from deeper geothermal fluids. Siderite concretions in the floodplain silts reflect the Fe-reducing conditions that developed as the surface became submerged beneath the water table. The pollen record captured both local and more regional vegetation, showing the prevailing dry rift valley climate despite development of the wetter conditions on the valley floor. The diatom record also suggests a dramatic change in local hydrology. The combined biological records of this semi-arid wetland indicate an abrupt change to wetter conditions, most probably as a result of a regional change in climate. Rift tectonics provided accommodation space, maintained the wetland at or below the water table and enabled spring recharge. The size of the modern wetland has been reduced by about 60% since 1969, which suggests that the system may now be under hydrological stress due to anthropogenic impacts from land-use change.

Keywords Kenya, Holocene, palaeoclimate, springs, wetland.

INTRODUCTION

Freshwater wetlands occur locally in arid to semi-arid regions of East Africa (Thompson & Hamilton, 1983; Crafter *et al.*, 1992; Hughes & Hughes, 1992). Many are ephemeral, associated with fluvial and deltaic settings (Mitsch & Gosselink, 2000). Others are longer lived and linked to geological structures such as faults or bedrock fracture systems that provide conduits for groundwater flow. Some faults tap deep aquifers that contain thermal water to produce hot springs; other springs derive water from shallow meteoric recharge and discharge as cool springs (Rosen, 1994; Renaut & Jones, 2000). There is no unifying classification of arid-region wetlands in Africa, and few geological studies focus on their sedimentary record (Hamilton & Taylor, 1986; Deocampo, 2002; Liutkus & Ashley, 2003). Consequently, there is a limited understanding of their origin, how they are sustained hydrologically and the type of sedimentary deposit that may be preserved in the geological record. The fragile ecology of wetlands may be affected by even minor changes in the hydrological regime or climate, so wetland records have the potential to be an important archive of palaeoclimate. Little attention, however, has been given to the processes that govern their formation, growth and demise. The importance of spring-fed wetlands goes beyond their historical record, as they are an important water resource in modern arid regions with burgeoning populations (e.g. Thenya, 2001).

Most low-latitude regions, and East Africa in particular, have been experiencing a long-term trend to increasing aridification over the last several million years (Cerling *et al.*, 1993; Cane & Molnar, 2001), although shorter wet-dry cycles driven by astronomic forcing appear to be superimposed on this long-term trend (Ashley, 2001; Trauth *et al.*, 2003). Hominid evolution took place in Africa during the Plio-Pleistocene, and climatic change is thought to have been an important contributing factor (e.g. deMenocal, 1995; Vrba, 1995; Potts, 1996). Consequently, the East African Rift has long been the focus of geological and palaeoclimatic research, and the Baringo-Bogoria region, located just north of the Equator (Fig. 1), has received considerable attention (e.g. Tiercelin, 1990; Renaut & Tiercelin, 1994; Hill, 2002). As part of a broader research effort to understand palaeoclimatic forcing and palaeoenvironmental response during the Quaternary, a small 1.5 km² freshwater wetland, the Loboï Swamp, was chosen for analysis (Ashley

et al., 2002a,b). An interdisciplinary study was conducted on the sedimentology, hydrology, pedology and biology of the wetland. The objectives of this paper are to: (1) describe the sedimentary record of Loboï Swamp and to interpret its origin and history; (2) assess the hydrology of the swamp and explain wetland plant distribution; (3) determine sedimentological features by which palaeowetlands can be recognized; and (4) predict the long-term health and longevity of the wetland given the present hydrological land-use conditions.

PHYSICAL SETTING

Geology and geomorphology

The Loboï Swamp is 3 km long and 0.3–0.5 km wide (≈ 1.5 km² in area). It is situated at 1000 m above sea level and just north of the Equator (0°22'N/36°03'E). Loboï Swamp lies at the southern margin of the Loboï Plain in the Baringo-Bogoria half-graben of the central Kenya Rift Valley (Fig. 2). The Loboï Plain (≈ 22 km long by up to 20 km wide) lies in the N–S axial depression of the rift and today separates Lake Baringo (≈ 970 m elevation) from Lake Bogoria (≈ 990 m) (McCall, 1967; Rosendahl, 1987; Renaut *et al.*, 2000). The drainage divide between the two lakes lies ≈ 3 km north of Lake Bogoria (Fig. 2). Surface drainage north of the divide flows towards Lake Baringo. Lake Baringo has remained fresh for several hundred years, whereas Lake Bogoria has been saline and alkaline. East and west of the Loboï Plain, the land surface rises abruptly as a series of fault-steps to form the Laikipia Escarpment and Tugen Hills respectively. The catchments for both lakes are composed mainly of Neogene basalts, trachytes and phonolites that are interbedded with fluvial, lacustrine and volcanoclastic sedimentary rocks.

The surficial sediments of the Loboï Plain are composed of stream channel (gravel and sands), overbank (K-feldspathic silts and clays) and sheetwash (sands and gravels) deposits of alluvial fan systems debouching from the adjacent uplands (Griffiths, 1977; Renaut & Owen, 1987). The rhomb shape of the modern Loboï Plain (Fig. 2A) and Lake Baringo reflects the tectonic control by two regional tectonic lineaments. The dominant N–S (N0–10°) trend follows that of the Tertiary–Recent Kenya Rift, whereas the NW–SE (N130–140°) trend that delineates the northern and

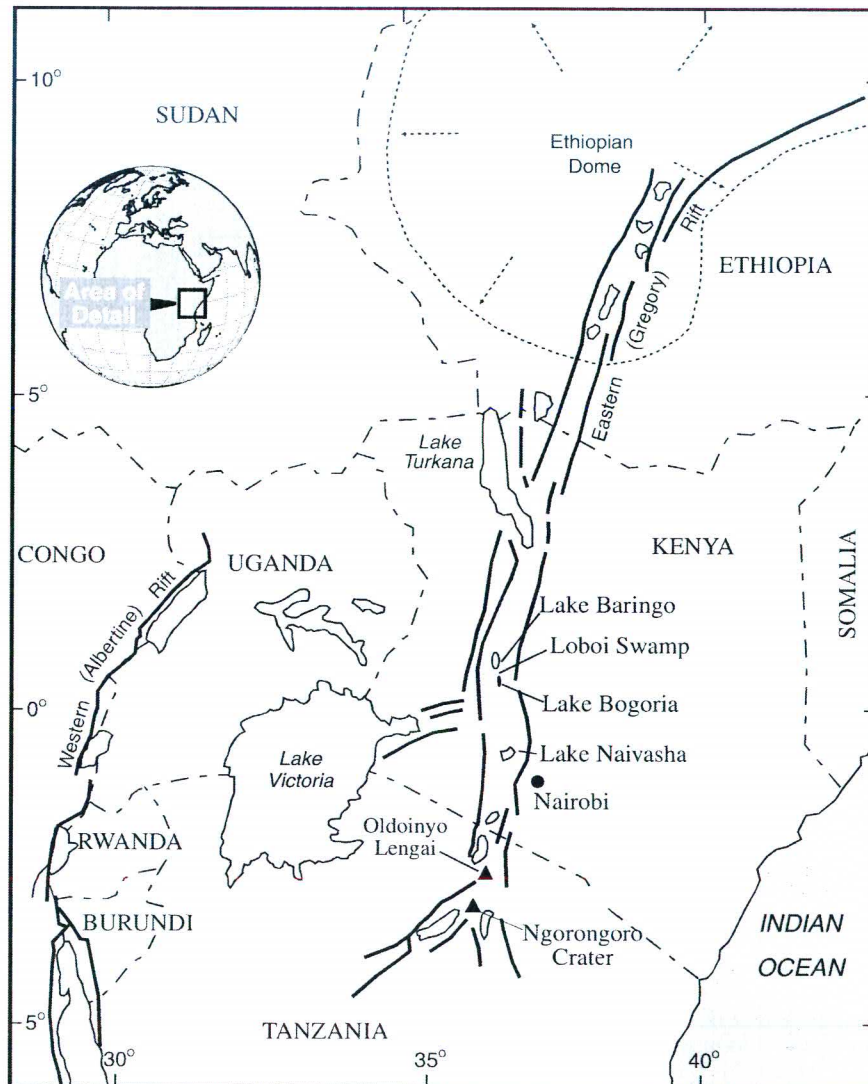


Fig. 1. General location of Lobi Swamp between Lake Baringo and Lake Bogoria within the Eastern (Gregory) Rift Valley, Kenya.

southern margins of the Lobi Plain is inherited from strong tectonic lineaments in the Precambrian–Cambrian (Mozambiquan) metamorphic basement rocks. These lineaments have been a major structural control on Cenozoic extension of the East African Rift (Le Turdu *et al.*, 1999; Atmaoui & Hollnack, 2003). The exposed siliciclastic sediments of the plain, of late Pleistocene to Holocene age, record the infilling of a deep axial trough that has undergone subsidence since the Palaeogene (Rooney & Hutton, 1977; Hautot *et al.*, 2000). Directly south of the plain, a lava field of the Pleistocene (< 1 Ma) Hannington trachyphonolites (Griffiths & Gibson, 1980) and subsidiary basalts forms the Bogoria Plateau,

which dips gently northwards. The plateau is densely grid-faulted with the development of many small grabens, half-grabens and horsts with throws of up to ≈ 50 m. These trachyphonolites are flexured below the Lobi Plain where they meet the NW–SE-trending Waseges–Marmanet Transverse Zone (WMTZ), which is rooted in basement rocks (Fig. 2A; Le Turdu *et al.*, 1999). The Lobi Swamp lies in a narrow, westward-tilted, graben-like structure adjacent to one of these fault blocks (Fig. 2B). The structural setting implies that the swamp and its underlying sediments may be underlain by downfaulted trachyphonolites at a relatively shallow (tens of metres) depth.

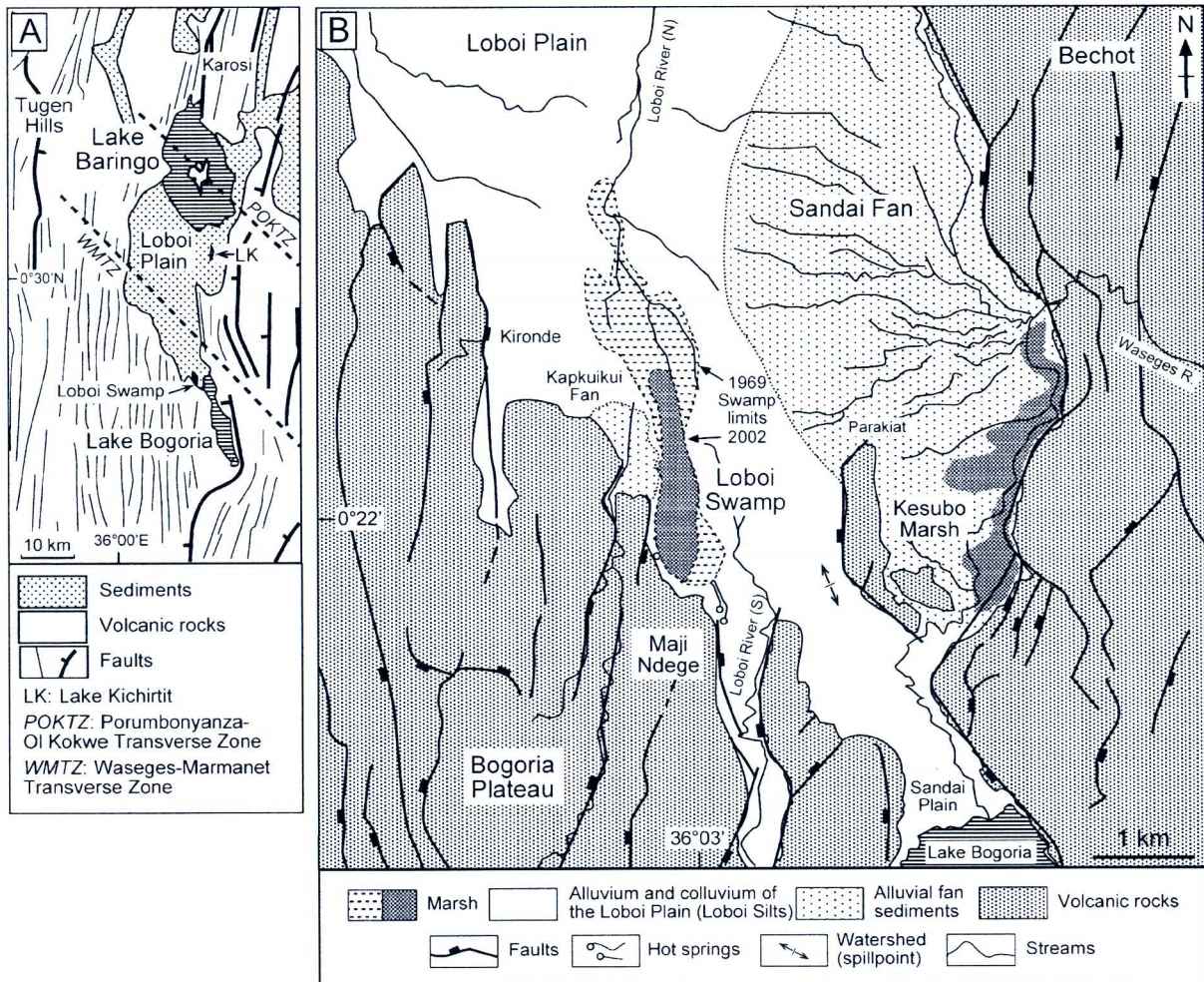


Fig. 2. (A) Structural setting of the Lobi Plain within the Kenya Rift. The alluvial plain is situated between two north-west- to south-east-trending transverse zones (tectonic lineaments) and a north- to south-trending fault system (after Hautot *et al.*, 2000). LK is the location of Lake Kichiritit, which formed in 1993–94. (B) Lobi Swamp is located immediately east of faulted volcanic bedrock and north of the drainage divide (watershed spill point) between Lake Bogoria and Lake Baringo. Lobi River (S) flows adjacent to, but not into, the wetland. The Kapkuikui alluvial fan on its western margin is built from sediments eroded from the Bogoria Plateau. The swamp drains northwards via Lobi River (N). The area covered by Lobi Swamp has decreased by $\approx 60\%$ since 1969.

Land use

According to local tradition, the most recent wave of immigration to the Lobi Plain occurred about 250–300 years ago, although the archaeological record of human occupation extends back to the Pleistocene (e.g. Farrand *et al.*, 1976). The early settlers from the adjacent hill country were pastoralists (Thom & Martin, 1983). Population growth and associated land-use changes led to a general degradation of the landscape including stripping of vegetation and major soil erosion (e.g. Snelder & Bryan, 1995; Mwasi, 2001; Johansson & Svensson, 2002).

Intensive agriculture was introduced to the Lobi Plain about 50 years ago, and cultivation has increased as more of the population have switched to subsistence farming.

Hydrology

The local region receives ≈ 700 mm year⁻¹ precipitation (25-year average) on the rift valley floor; potential evaporation exceeds 2500 mm (Fig. 3A) (LaVigne & Ashley, 2001). Mean annual temperature is 23–25 °C. Annual precipitation is dominated by monsoons, with the highest precipitation in April followed by a secondary peak in

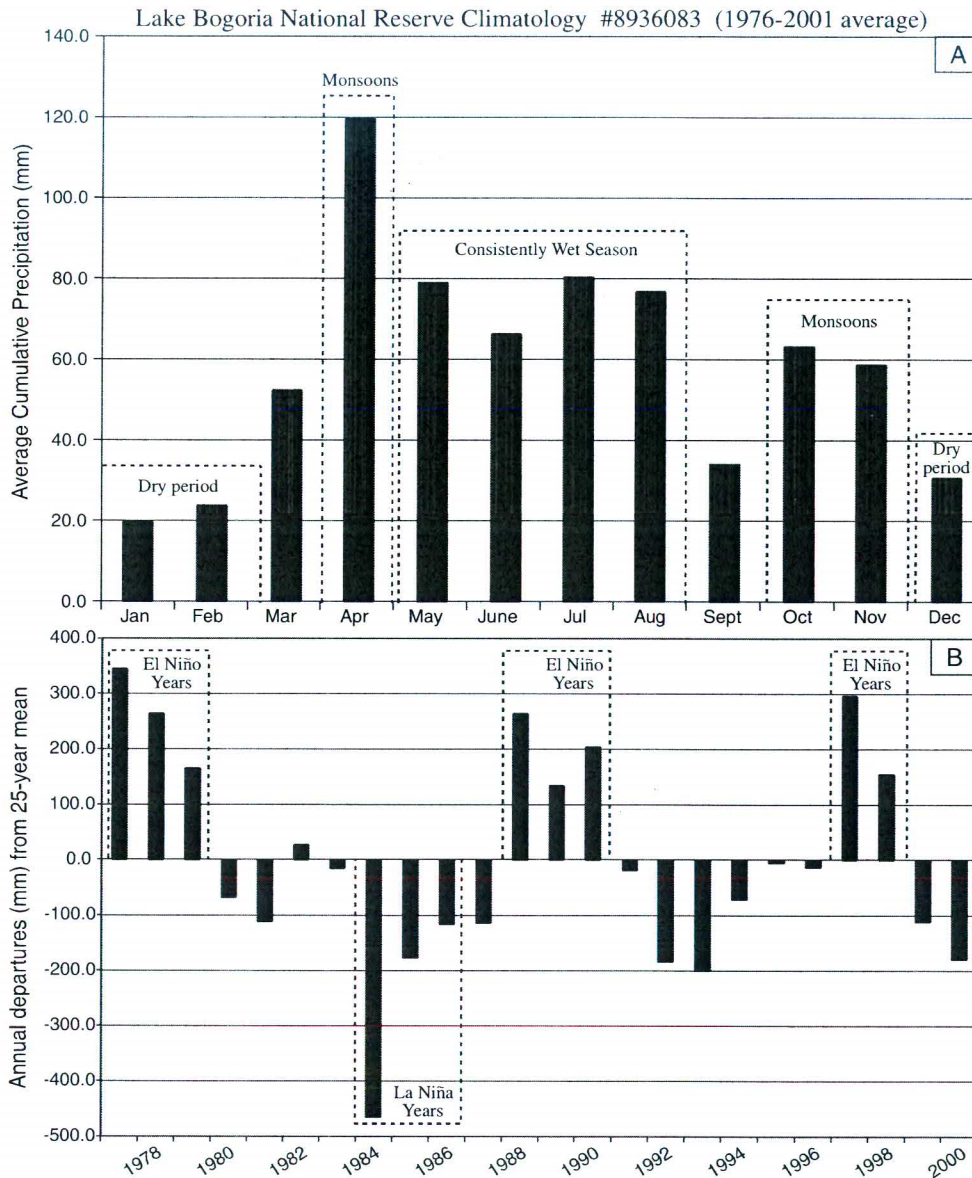


Fig. 3. (A) Rainfall seasonality (25-year average) at Bogoria Natural Reserve weather station (8936083) located 2 km south-east of Loboï Swamp. Highest precipitation occurs in April and October–November, and is related to monsoons. December to February is dry; May to August precipitation results from late afternoon cloudbursts. (B) Long-term rainfall variability (deviation from the 25-year mean) reveals wetter periods coinciding with El Niño events and drier periods coinciding with La Niña (LaVigne & Ashley, 2001).

November (Rowntree, 1989). Afternoon cloudbursts during the months May to August create sheet run-off and flashy river discharge. El Niño and La Niña events have been interpreted from analyses of the 25-year records from local weather stations (LaVigne & Ashley, 2001; Johansson & Svensson, 2002; Harper *et al.*, 2003). A plot of 'deviation from the mean' of the rainfall reveals 5–7 year cycles of interannual variability (Fig. 3B).

The Loboï River (S) drains from volcanic terrain (on the west side of Lake Bogoria) northward to the Loboï Plain. The Loboï River (N) drains northward from the swamp and ultimately flows into Lake Baringo (Fig. 4). Loboï Swamp, just north-west of the drainage divide between the two large rift lakes (Fig. 2B), acts as a large 'sponge' by retaining water and moderating its flow and is a habitat for crocodile and over 100 species of birds. The swamp is fed by

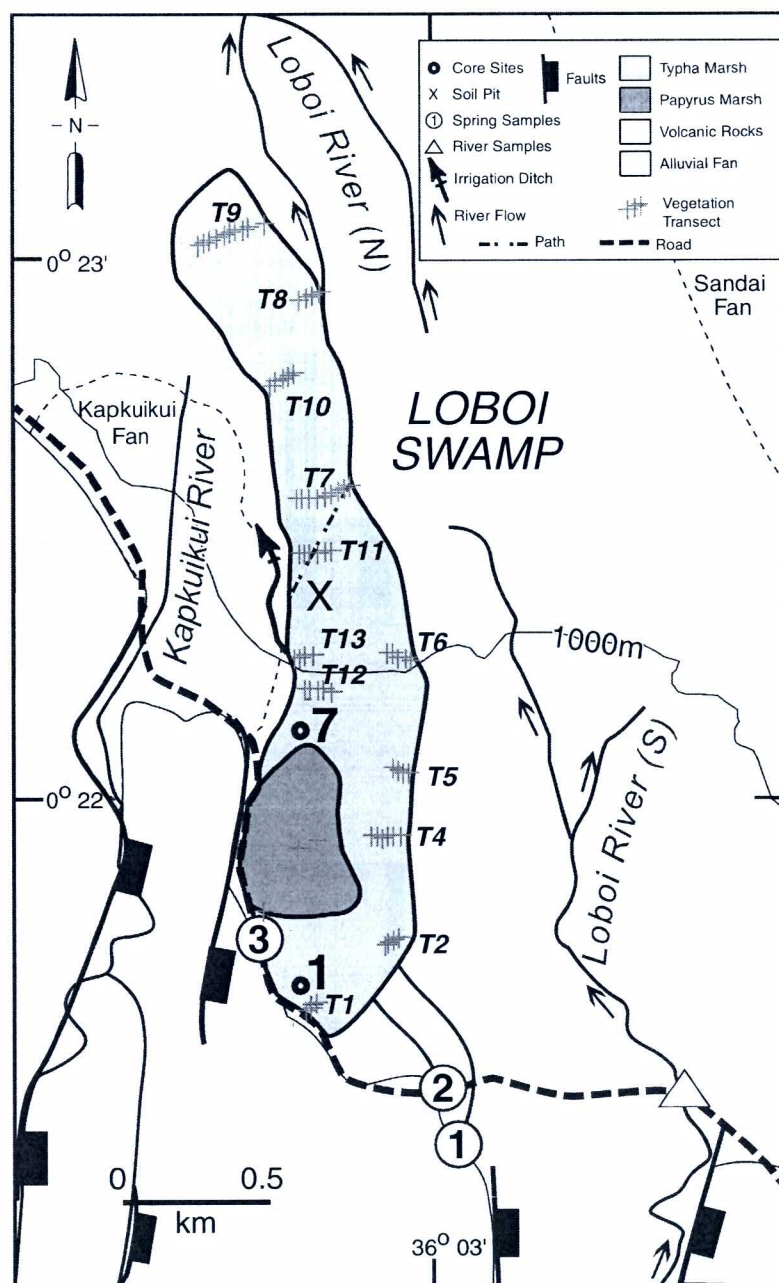


Fig. 4. Map of Loboï Swamp with spring sample sites: 1. Lake Bogoria Hotel Spring; 2. Chelaba Spring; 3. Turtle Spring; river sample sites, core locations, vegetation transects and general pattern of vegetation. Irrigation ditch drains north-westwards along the toe of the Kapkuikui Fan.

two large warm springs (Lake Bogoria Hotel Spring and Chelaba Spring) at its southern end (Fig. 4). A smaller spring, Turtle Spring, discharges to the west of the swamp, together with many small seeps. These three springs were flowing into the swamp in 1888 (Von Hohnel, 1891, p. 8). The combined discharge of the two large springs into the swamp is $0.35 \text{ m}^3 \text{ s}^{-1}$. All springs lie on N-S faults (Fig. 2B). Other springs probably discharge within the wetland,

particularly in the area of papyrus growth, but their presence has not been verified. A drainage ditch was dug at the edge of the swamp on the distal end of Kapkuikui Fan in 1970 to irrigate agricultural fields (Fig. 4). The discharge in the ditch is $0.035 \text{ m}^3 \text{ s}^{-1}$. In 2002, flow from the Loboï River (S) flowed adjacent to the swamp (Fig. 2), but avulsed into the Sandai River during a flood event and now drains into Lake Bogoria (Harper *et al.*, 2003).

METHODS

Wetland vegetation was studied along line transects from the swamp edge towards the centre, and all species encountered were recorded (Fig. 4). Transect lengths ranged from 100 to 300 m based on accessibility (water depth and vegetation density). Representative samples were collected, dried and archived at the East African Herbarium, National Museums of Kenya, in Nairobi.

Water samples were collected from the Lobo River, springs entering the swamp, an irrigation ditch draining the swamp and at each of the coring sites (Fig. 4). Water-quality parameters [temperature, pH, conductivity and dissolved oxygen (DO)] were measured with portable field instruments, calibrated in the field. Aliquots of surface waters were filtered in the field using 0.2 µm filters for major cation and 0.45 µm filters for anion and total alkalinity (Alk_T) splits. The cation aliquot was acidified with trace metal-grade (Optima) concentrated nitric acid. The Alk_T analyses were completed on site within 48 h of collection by potentiometric titration using a manual Contriburette (10 µ) burette and Orion 520A pH meter. Titration data were reduced using the USGS online program ALKALINITY CALCULATOR (Rounds, 2003). Cations were analysed on a Leeman Laboratories DRE sequential dual-view ICP-AES and anions by Dionex-500 IC, with anion-14 column suppressed conductivity detection and Na-carbonate element.

Seven cores (2.5 cm wide and 1.5–4 m long) were extracted from the wetland using a hand piston corer. Six cores were taken in the vicinity of core 1. Core locations were recorded using a global positioning system (GPS). Sediment compaction during coring was experienced at all sites, so a simple linear extrapolation was used to 'decompact' the core data for presentation. Depth values in this paper have been adjusted for compaction, which ranged from 1 to 3 cm. Sedimentation rates were determined using unstable isotope Pb²¹⁰ (Appleby & Oldfield, 1978). Analysis of Cs¹³⁷ concentration in sediments was attempted, but Cs fall-out to this equator site was not sufficient for dating.

Two representative cores (cores 1 and 7) were selected for analysis (Fig. 4). They were split and described using the methods of Birks & Birks (1980), X-radiographed and scanned for magnetic susceptibility using a Geotek multisensor core logger (Lamont Doherty Earth Observatory). Samples for lithology, diatoms and geochemistry were collected every 10 cm. Carbonate fraction was

removed with dilute HCl. Grain-size analysis was carried out by sieving and pipette analysis; loss-on-ignition at 550 °C (LOI) was determined according to the procedures of Heiri *et al.* (2001); stable carbon isotopes of soil organic matter (SOM) were analysed using a Finnigan-MAT DELTA Plus mass spectrometer; bulk and clay mineralogy (< 2 µm) were determined by X-ray diffraction methods (General Electric XRD-5 diffractometer with CuK_α radiation, Ni filter and scintillation detector); C and N analyses of organic matter in sediment were determined on carbonate-free sediments using a Carlo Erba NA 1500 series II elemental analyser. The percentage carbon is distinctly different between the two analytical methods, LOI and elemental analyses. LOI measurement includes all volatile components that can be removed by heating to 550 °C. This can include N, S, OH in clay minerals and waters of hydration in clays or other minerals and on organic surfaces. The C measurement determined by elemental analyses reflects only true organic carbon.

Pollen samples were prepared using standard procedures (Faegri & Iversen, 1989). A sample size of 1 cm³ with an interval of 5 cm was used. Thirty-six levels were counted using a Leitz Laborlux 12 microscope at 400× magnification. Pollen was identified using the extensive pollen reference collection at the National Museums of Kenya. The average pollen sum per level was 430 grains. Diatoms were examined on smear slides after being mounted in Styra, with a total of 400 diatoms counted per slide. Diatom identification was carried out at 1000× magnification and is based on the work of Gasse (1986, 1987). Dating of the record was by radiocarbon using organic material at 93–95 cm depth (core 1).

RESULTS

Modern vegetation

The Lobo Swamp is characterized by cattail (*Typha domingensis* Pers.), which forms a wide belt encircling an 'island' of papyrus (Figs 4 and 5A). Areas with *Typha* are seasonally flooded and comprise most of the plant species diversity (Fig. 5B, Table 1) (Muasya *et al.*, 2004). Papyrus (*Cyperus papyrus* L.) grows in permanently inundated areas (Fig. 5C). It is the dominant emergent vegetation in wetlands of tropical Africa (Hughes & Hughes, 1992). Papyrus is rooted on the edge of water bodies or occurs as a floating mat on

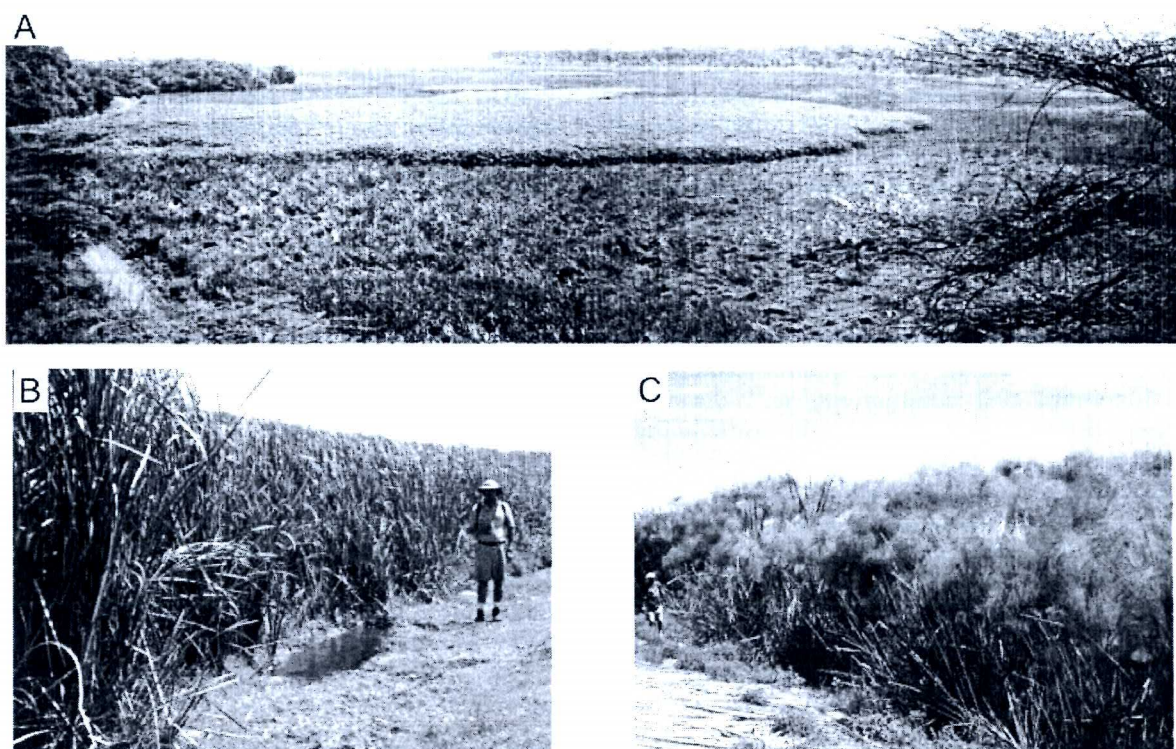


Fig. 5. (A) Overview of Loboï Swamp; raised area is floating papyrus vegetation. (B) *Typha domingensis* Pers. comprises $\approx 80\%$ of the modern wetland. (C) *Cyperus papyrus* L. makes up the remaining $\approx 20\%$ of the wetland. Papyrus culms (stems) and umbels (flowering portion) may reach 5 m high. Culms are used by local people for roofs and mats; drying culms are on the ground.

Table 1. Common vascular plants recorded in the *Typha* (T) and papyrus (P) zones of Loboï Swamp.

Family	Species	Zone
Convolvulaceae	<i>Ipomoea aquatica</i> Forsk.	T
Cyperaceae	<i>Cyperus laevigatus</i> L.	T
Cyperaceae	<i>Cyperus papyrus</i> L.	P
Cyperaceae	<i>Pycnus mundtii</i> Nees	T
Lemnaceae	<i>Lemna perpusilla</i> Torrey	T/P
Onagraceae	<i>Ludwigia leptocarpa</i> (Nutt.) Hara.	T
Papilionaceae	<i>Vigna luteola</i> (Jacq.) Benth.	T/P
Poaceae	<i>Echinochloa pyramidalis</i> (Lam.) Hitchc.	T
Poaceae	<i>Leersia hexandra</i> Sw.	T
Typhaceae	<i>Typha domingensis</i> Pers.	T

water up to 1.5 m deep. Papyrus and reeds (presumably *Typha*) were reported from the swamp by Von Hohnel (1891), who visited the area in 1888.

Papyrus culms (stems) and umbels (flowering portion) may together reach 5 m in height. Unlike most emergent wetland vegetation, papyrus has

the C₄ pathway of photosynthesis (Jones & Milburn, 1978). The swamp is surrounded by vegetation typical of a semi-arid climate, with *Acacia* scrubland on the uplands and salt-tolerant grasses such as *Sporobolus spicatus* on the plains. The drier portions of the swamp are used for cattle grazing. Papyrus culms are harvested locally and dried for roofs and matting.

Aqueous geochemistry

The Loboï River (S), sourced in volcanic uplands west of Lake Bogoria, is supplemented by discharge from several springs before it reaches the southern Loboï Plain. The river water is well aerated (DO = 7.3 mg L⁻¹), alkaline pH (8.3), with total dissolved solids (TDS) of ≈ 0.56 g L⁻¹ (Table 2).

The Loboï springs discharge along N–S faults along the south-western margin of the Loboï Plain (Fig. 4) and are the primary sources of water for Loboï Swamp. The spring waters are relatively warm (35–36 °C), moderately oxygenated

Table 2. Chemical analyses of surface water from the Lobo River, warm springs and Lobo Swamp.

Sample identification	Temp. (°C)	pH	DO (mg L ⁻¹)	Cond. (mS cm ⁻¹)*	TDS (g L ⁻¹)†	Na ⁺ (mg L ⁻¹)‡	K ⁺ (mg L ⁻¹)	Ca ²⁺ (mg L ⁻¹)	Mg ²⁺ (mg L ⁻¹)	SiO ₂ (mg L ⁻¹)	Cl ⁻ (mg L ⁻¹)	F ⁻ (mg L ⁻¹)	NO ₃ ⁻ (mg L ⁻¹)	SO ₄ ²⁻ (mg L ⁻¹)	Alk _T as HCO ₃ ⁻ (mg L ⁻¹)	GPS Lat.	GPS Long.
Lobo River	23.2	8.3	7.3	0.56	0.56	116	13.0	13.5	1.90	68.5	9.64	4.57	4.16	12.0	365	N00° 21'451"	E036° 03'480"
Inflow to swamp																	
Warm springs†																	
1. Lake Bogoria Hotel	36.2	6.32	3.9	0.60	0.57	132	14.9	6.45	1.39	88.2	14.1	3.30	8.10	15.3	338	N00° 21'372"	E036° 03'052"
2. Chelaba Spring	36.4	6.42	3.6	0.61	0.54	118	16.7	6.92	1.69	85.8	10.2	3.70	5.40	12.0	323	N00° 21'481"	E036° 03'016"
3. Turtle Spring	34.9	6.79	3.5	0.62	0.56	124	16.9	7.67	1.95	83.8	7.10	2.40	3.80	7.70	351	N00° 21'749"	E036° 02'690"
Outflow from swamp																	
Irrigation ditch	22.5	7.39	1.1	0.69	0.66	144	18.6	8.56	1.96	75.3	12.1	4.10	1.40	3.70	426	N00° 22'475"	E036° 02'638"
Swamp surface water																	
Typha marsh, core site 1	27.3	7.47	1.1	0.66	0.65	140	17.8	7.38	1.86	88.3	9.10	4.30	1.50	9.50	416	N00° 21'625"	E036° 02'778"
Typha marsh, core site 7	20.2	8.03	0.20	1.67	1.52	276	78.8	40.5	12.6	95.6	57.2	6.10	5.30	47.6	958	N00° 22'081"	E036° 02'723"

*mS cm⁻¹ = milli Siemens cm⁻¹ = mmohs cm⁻¹.

†TDS (total dissolved solids) calculated from the chemical analyses.

‡Numbers refer to labels in fig. 4.

(DO = 3.5–3.9 mg L⁻¹) and slightly acidic (pH = 6.4–6.9) (Table 2). These moderately fresh waters (\approx 0.54–0.57 g L⁻¹ TDS) are used extensively for drinking and irrigation. In contrast, water draining from the marsh and surface water within the marsh are poorly aerated (DO = 0.2–1.1 mg L⁻¹), have higher pH (7.4–8.3) and are generally more saline (TDS = 0.66–1.5 g L⁻¹) than the springs (Table 2).

Lithological record

Cores

Core 1 is located in the spring-proximal part of the wetland where wetland sediments are the thickest, i.e. \approx 1 m thick (Figs 4, 6 and 7). Core 7 is about 1 km from the major springs (Lake Bogoria Hotel and Chelaba), 1 km from the Lobo River (S) and immediately adjacent to the Kapkuikui River alluvial fan. The peat is thin (0.1 m) despite the fact that the *Typha* is nearly 3 m high at the site (Fig. 5B).

Core 1 is 2 m long and fines upwards from sandy silt to organic-rich clay gradually and then to peat abruptly (Fig. 7). X-radiographs reveal vaguely bedded detrital sediments at the base and dense, fibrous root structures in the peat. The bedding is composed of thin layers (1–3 cm) of sandy silt and silty clay composed of mostly smectite-rich clay and minor illite-rich clay, kaolinite, K-feldspar and traces of plagioclase feldspar. Thin (0.5 cm) bands of siderite concretions are also present. In the organic-rich clay and peat intervals, the feldspar, illite-rich clay and kaolinite are much less abundant and the

smectite-rich clay less crystalline. Jarosite [KFe₃⁺³(SO₄)₂(OH)₆] was identified in some peat samples, and siderite occurs as disseminated nodules (0.2–1 cm). LOI data show an increase in organic matter upsection from <5% to 40% at the top. Organic carbon increases from 0 to 20%, whereas nitrogen increases from 0 to 2%. Magnetic susceptibility is nearly 200 SI in the detrital material at the bottom, but decreases to nil in the organic-rich clay and peat (Fig. 7).

Core 7 is 4 m long and is composed mainly of detrital sediments with a thin (0.1 m) cap of peat at the top (Fig. 8). The sediments consist of alternating discrete beds varying in grain size from coarse to medium sand to silty clay and clay. Overall, the sediments fine upwards. The mineralogy consists of K-feldspar and plagioclase feldspar, poorly crystalline smectite-rich clay, illite-rich clay and kaolinite. The sands have iron-bearing minerals (magnetite and hornblende) and their weathering products (haematite, etc.). This composition is reflected in the high magnetic susceptibility readings of 500–700 SI. Root markings are common in the finer units, and siderite occurs as finely disseminated concretions and discrete horizontal bands.

Soils

A 1 m deep soil pit excavated at the thinning distal portion of the Lobo Swamp (Figs 4 and 6) consists of 35 cm of wetland deposits that sharply overlie > 65 cm of buried floodplain deposits with a weakly developed Inceptisol (Driese *et al.*, 2004). The wetland deposits are silty clay to clayey silt dominated by roots and rhizomes of

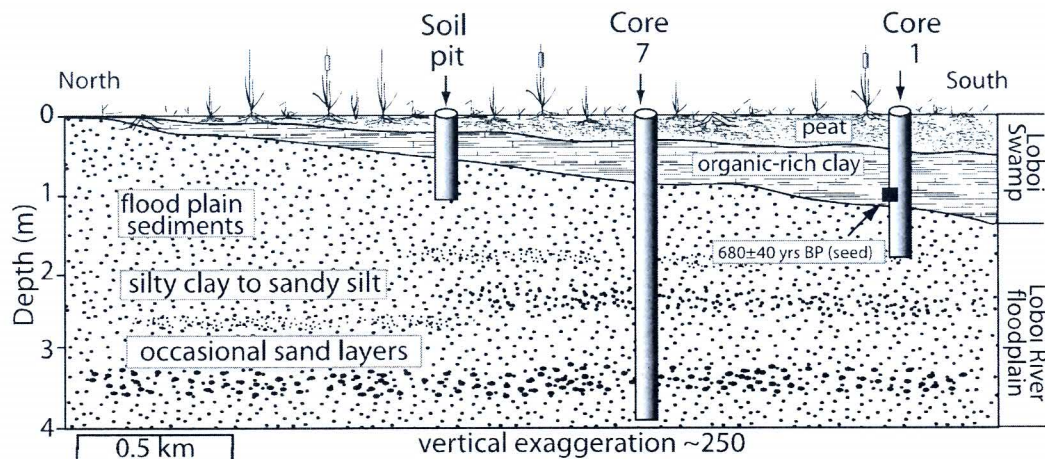


Fig. 6. Schematic north-south cross-section of Lobo Swamp illustrating the northward thinning of peat and organic-rich clay deposits overlying Lobo River floodplain sediments in relation to positions of coring sites and soil pit (modified from Driese *et al.*, 2004).

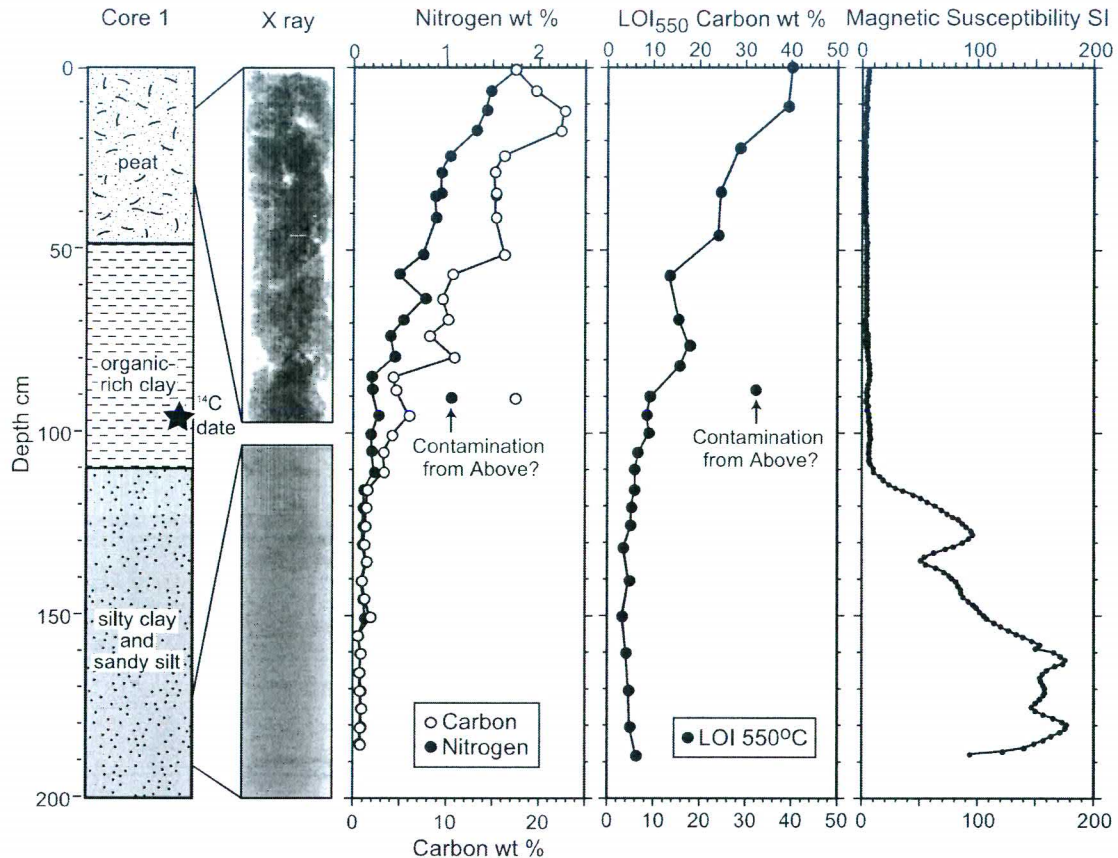


Fig. 7. Lithological record of core 1 from the spring-proximal part of the wetland, showing Lobi floodplain sediments overlain with incipient wetland deposits (organic-rich silt) capped with wetland peat. Location of ^{14}C date is indicated (Table 3). X-radiographs reveal structures in the peat and floodplain sediments. Location of core 1 shown on Figs 4 and 6.

Typha. They consist of, in descending order from the soil surface, organic C-rich O (surface litter) and A horizons, underlain by two Bt horizons enriched in pedogenic clays. The buried floodplain deposits (Bw1b and Bw2b horizons) comprise sandy, lower organic content deposits of clayey silt and fine- to very fine-grained volcanic sand that contain weakly developed pedogenic features, such as illuviated clays and weathered grains, as well as root traces of grasses and partially decomposed, woody *Acacia* roots. The wetland soil consists of both biologically produced materials (organic matter, diatoms), as well as fine terrigenous material derived from flood events and trapped by the dense vegetation and captured as dust aerosols (Driese *et al.*, 2004).

Chronology

Organic material collected near the base of the organic-rich clay at 93–95 cm (core 1) produced a conventional radiocarbon age of 680 ± 40 BP (Beta-172862) (Figs 6 and 7, Table 3). Radiocarbon

ages are calibrated to calendar years (cal year BP) using the program of Stuiver *et al.* (1998), and the two sigma age range is reported (Table 3). The average sedimentation rate as determined by C^{14} is $1.38 \text{ mm year}^{-1}$; however, as the wetland deposits have an increasing proportion of organic sediment to mineral sediment, particularly from 35 cm to surface, this calculation is probably on the high side. Pb^{210} activities measured in samples from the top 27 cm of core 1 indicate that there is a mixing depth of 7–8 cm and that, below this layer, the decrease in activity with depth generates a more realistic particle accumulation rate of about 0.9 mm year^{-1} . This accumulation rate is considered an approximation because the Pb^{210} activities ($\approx 3000 \text{ pCi kg}^{-1}$) in the wetland sediments are only 30% of those typically used for dating lake sediments (Appleby & Oldfield, 1978). The 7–8 cm mixing depth is equivalent to ≈ 80 years. Root material at 309 cm depth (core 7) yielded an essentially modern age (Table 3). Attempts to use Cs^{137} as a dating tool on the sediment cores were

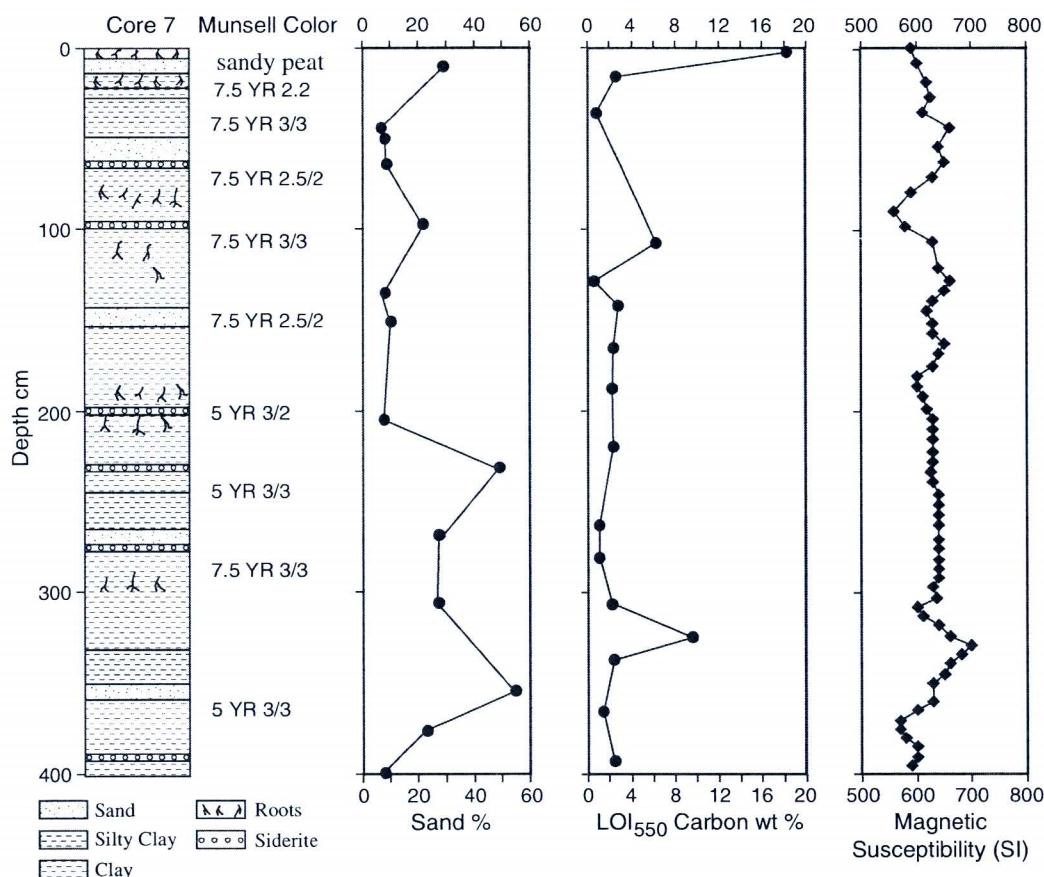


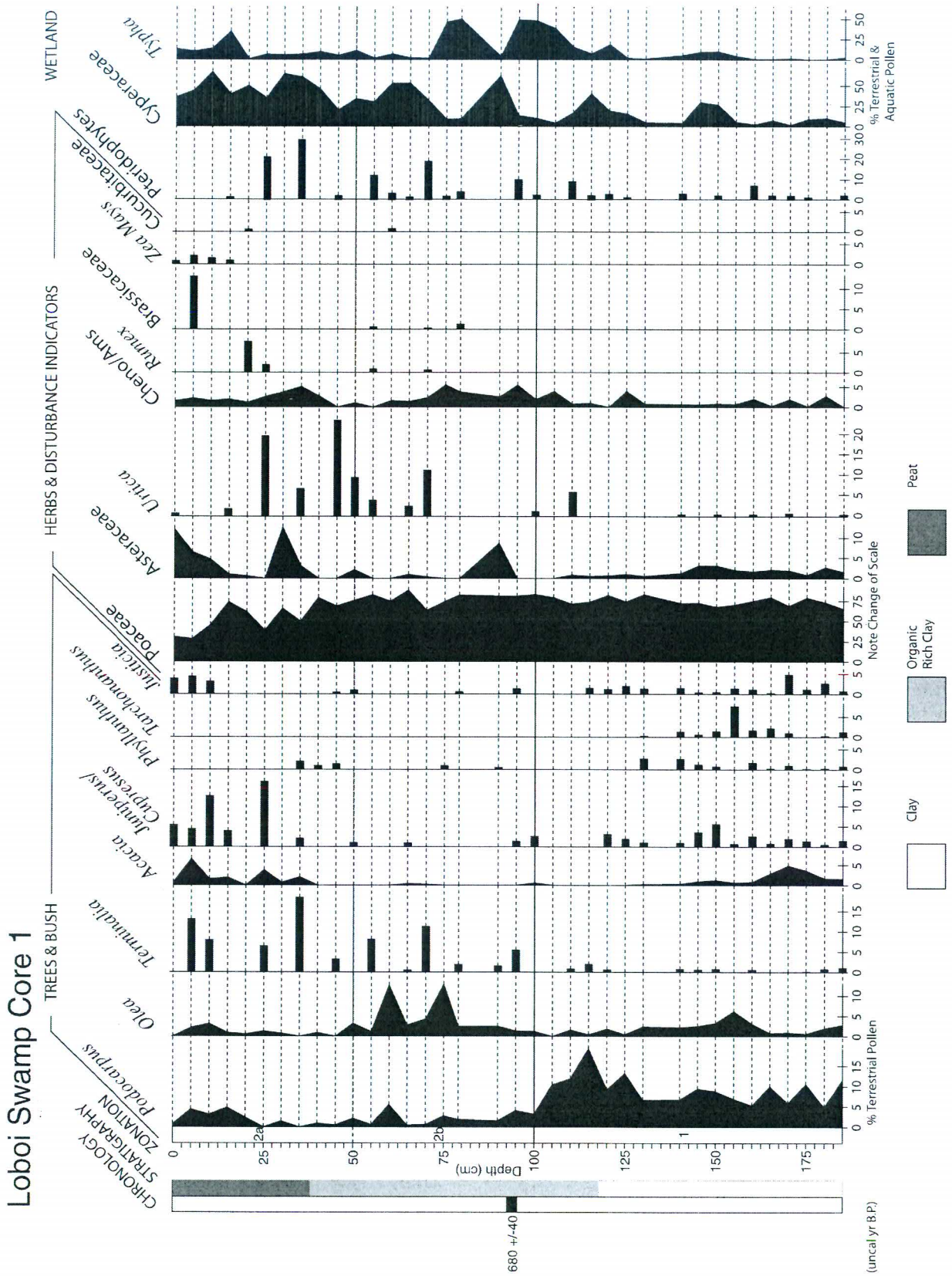
Fig. 8. Lithological record of core 7 from the spring-distal part of the wetland, composed mainly of floodplain sediments with a thin capping of sandy peat. Root material from 309 cm depth was dated at 135 BP (Table 3). Percentage carbon (LOI 550 °C) is insignificant except in the peat. Location of core 7 shown on Figs 4 and 6.

Table 3. AMS radiocarbon dates from Lobo Swamp.

Beta Lab. no.	Sample label	Sample depth (cm)	Measured radiocarbon age	¹³ C/ ¹² C ratio (‰)	Conventional radiocarbon age	Calibrated intercept (BP)	Two sigma calibrated range (BP)	Comments
172859	LM02-7-5-309	309	135.6 ± 0.6pMC	-24.4	135.5 ± 0.6pMC	NA	NA	Root material (<i>Acacia</i> ?)
172862	LM02-1-2-93-95	93-95	520 ± 40	-15.1	680 ± 40	660	680-630 600-560	Plant material

pMC, percentage modern carbon. Analysed material is less than 50 years old. The program used for calibration is INTCAL98 radiocarbon age calibration (Stuiver *et al.*, 1998).

Fig. 9. Stratigraphy, chronology and pollen data for Lobo Swamp. Pollen taxa present within the core (but not continuously from level to level) are graphed as bars. The pollen diagram from core 1 is divided into two main vegetation assemblages: zone 1 and zone 2. In zone 1, the terrestrial pollen is dominated by high Poaceae pollen (≈ 70%), relatively high *Podocarpus* pollen (14%) and the consistent presence of bush taxa (*Tarchonanthus*, *Phyllanthus* and *Justicia*). Zone 2 is characterized by the increased importance of wetland taxa (≈ 55%) and the decline in montane taxa (7%), dramatically illustrated by the precipitous decline in *Podocarpus* (≈ 2%). The zone is divided into two subzones (a and b) based upon a decline in Poaceae and the presence of pollen indicative of human disturbance and the appearance of *Zea mays* and Brassicaceae.



unsuccessful. Caesium fall-out is low near the equator, and large volumes of sediment (kilograms) would be required for analysis.

Biological record

Pollen

Pollen analysis was undertaken on sediments from cores 1 and 7; however, core 7 sediments were essentially devoid of pollen, except in the top 20 cm. The pollen diagram for core 1 is divided into two main vegetation assemblages (zones 1 and 2) based on change in the proportion of key taxa (Fig. 9). In zone 1 (190–100 cm), the terrestrial pollen is dominated by high Poaceae pollen ($\approx 70\%$), relatively high *Podocarpus* pollen (14%) and the consistent presence of bush taxa (*Tarchonanthus*, *Phyllanthus*) and herbs (Asteraceae and Chen/Ams). Using a conservative sedimentation rate of 1.0 mm year^{-1} for the lower portion of the core (0.94–1.8 m), this zone would represent ≈ 1540 –680 year BP. Montane taxa, which include *Podocarpus*, *Juniperus*, *Olea*, *Hagenia* and *Myrica*, comprise $\approx 18\%$ of the terrestrial pollen sum; wetland taxa, in contrast, calculated as a function of the total pollen sum, comprise $\approx 20\%$ of the record. The relatively high percentages of montane taxa are not indicative of the taxa growing near the site, but rather long-distance pollen dispersal. Zone 2 (≈ 100 –0 cm: 680 year BP–present) is characterized by an increased importance of wetland taxa ($\approx 55\%$) and a decline in montane species (7%), dramatically illustrated by the precipitous decline in *Podocarpus* ($\approx 2\%$). The zone is divided into two subzones based upon a decline in Poaceae and the presence of pollen indicative of human disturbance. The terrestrial pollen from subzone 2b (100–50 cm: 680– ≈ 360 BP) is characterized by continued high percentages of Poaceae ($\approx 78\%$), the decline in *Podocarpus* and pollen from Cyperaceae and *Typha* ($\approx 50\%$). *Urtica* and *Terminalia* are important terrestrial taxa; subzone 2a is characterized by the appearance of *Zea mays*, Brassicaceae, the increased importance of pollen from the Asteraceae family and a marked increase in *Juniperus/Cupressus* pollen.

Diatoms

Diatom analysis was conducted on cores 1 and 7. Core 7 located near the Kapkuikui alluvial fan contained only a few scattered and broken frustules. In core 1, diatoms are absent or occur as

rare fragments below 102 cm, except at 110–112 cm where they are common, and *Achnanthes exigua* reaches its highest frequencies in the core (coinciding with the basal part of an organic-rich clay) (Fig. 10). Diatoms are uncommon between 102 and 73 cm, common from 73 to 20 cm and abundant in the upper 20 cm. This general rise in diatom abundance is reflected in an overall increase in the percentage of *Rhopalodia gibberula* and its variety *protracta*.

The second most frequent taxon is *Diploneis subovalis*, which forms a common constituent throughout the diatomaceous parts of the core. *Nitzschia amphibia*, *N. communis*, *N. kuetziniana* and *N. palea* are present, together with other less frequent *Nitzschia* spp. In general, *Nitzschia* spp. decrease upwards, except between about 56 and 38 cm, where *N. amphibia* becomes dominant.

DISCUSSION

Geological record

Before this study, it was generally assumed that the Lobo Swamp was several thousand years old and had the potential to provide a regional palaeoclimatic record independent of the poorly constrained Holocene record obtained from cores in Lake Bogoria (cf. Tiercelin *et al.*, 1982; Tiercelin & Vincens, 1987; Renaut & Tiercelin, 1994). However, the C^{14} date obtained near the base of organic-rich clay in core 1 (Fig. 7) shows that the present Lobo Swamp is a very young geological feature.

The wetland lies on the northward extension of a narrow westerly dipping tilt block or small graben-like structure at Maji Ndege that affects the Hannington trachyphonolites and passes below the alluvial sediments of the Lobo Plain (Fig. 2A). Differential subsidence of the buried tilt block may have occurred following movement along the fault(s) located directly west of the swamp. Westerly tilting and subsidence of the buried fault block could have lowered the land surface sufficiently to bring the water table at or close to the surface about 700 years ago and maintained the wetland since then.

The juxtaposition of surface drainage and wetlands adjacent to fault scarps is common throughout the Baringo–Bogoria region and elsewhere in the rift. The Kesubo Marsh and Sandai River, for example, similarly lie adjacent to the Bechot–Siracho fault scarp (Fig. 2B). The southward

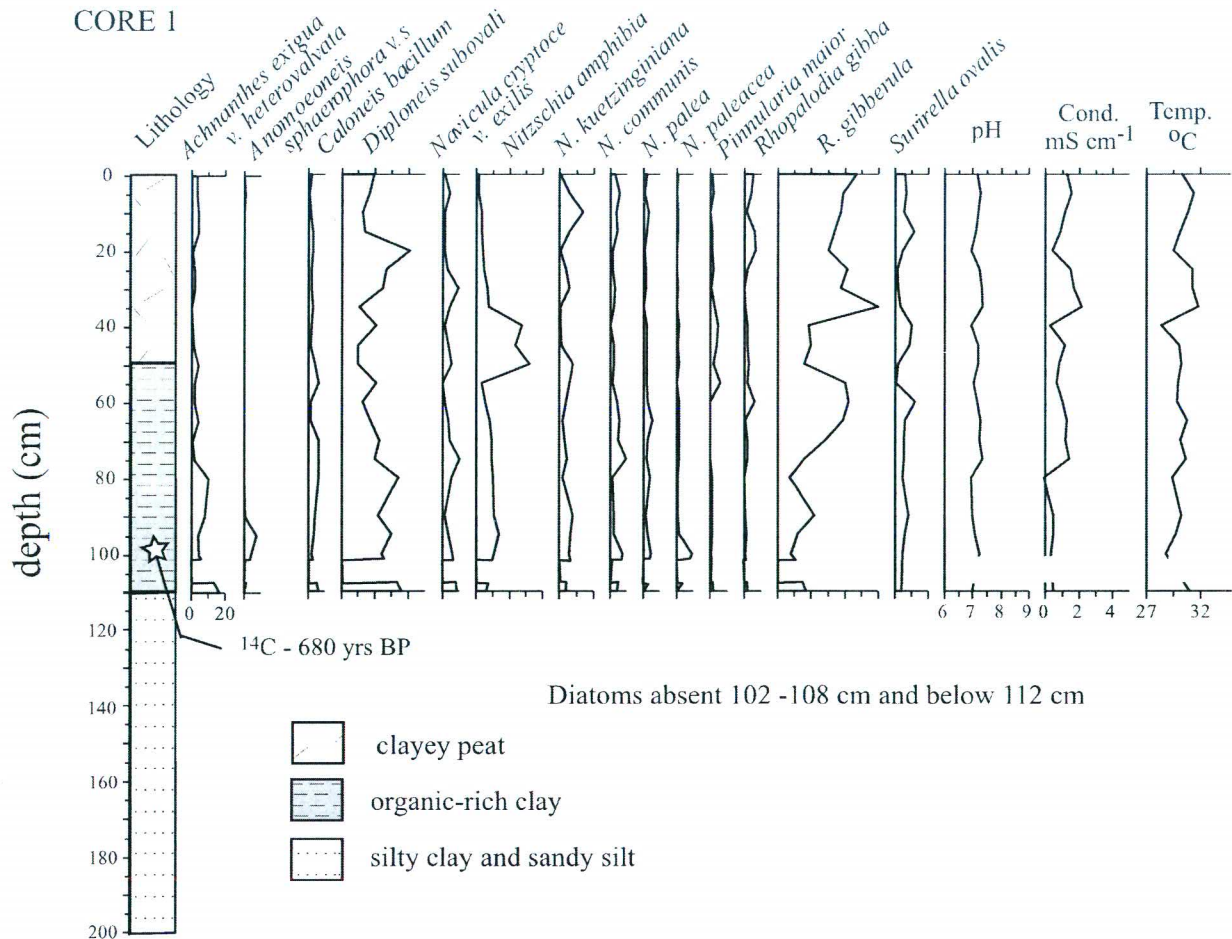


Fig. 10. Diatom stratigraphy of core 1. Only diatoms forming >5% in at least one sample are shown. Diatoms are uncommon between 102 and 73 cm, common from 73 to 20 cm and abundant in the upper 20 cm. X-axis for each species is percentage of total flora. Parameters to the right are based on inference models using modern diatom floras from the area (Owen *et al.*, 2004). The diatom record suggests an abrupt change in hydrology at ≈ 100 cm depth with sufficient permanent water to support diatoms. Interpretation of the diatom assemblage suggests broadly stable water chemistry during the existence of the swamp.

diversion of the Sandai River towards Lake Bogoria and the development of the Kesubo Marsh probably reflect differential subsidence on the southern part of the Sandai Fan directly adjacent to the scarp (Renaut, 1982, 1993).

Recent fault movements and subsidence are common throughout the Baringo–Bogoria region. Although seismic activity is common (Young *et al.*, 1991; Tongue *et al.*, 1994), the last major local earthquake (Subukia: M 6.9) occurred in 1928 (McCall, 1967; Ambraseys, 1991). Evidence for neotectonic tilting of strata on the Lobo Plain is seen 15 km north-west of the wetland (Le Turdu *et al.*, 1995, their fig. 4B).

An alternative explanation is that the swamp originated by drainage diversion without direct tectonic influence. During a period of exceptionally heavy rainstorms in 1993–4, a river diversion

took place on the eastern margin of the Lobo Plain and created a new wetland that has since become a shallow freshwater lake, now named Lake Kichirtit (Fig. 2A). When visited in July 1995, the lake was elongate, ≈ 3 km long by 1 km wide and up to at least 1 m deep with an extensive zone of wetland vegetation (> 250 m) already well established around its margins. Its Na–Ca–HCO₃ waters were fresh (585 mg L⁻¹ TDS), alkaline (pH 8.25) and had a salinity about twice that of local streams. The lake has since stabilized and is recharged by ephemeral stream flow and shallow groundwater seepage but, unlike Lobo, there is no inflow from thermal springs. Lake Kichirtit may not persist for long. Although drainage diversion induced by heavy rainfall is an unlikely explanation for the Lobo Swamp, the ‘overnight’ formation of Lake Kichirtit

demonstrates that wetland sediments on rift floors may be localized and have diverse origins, and that abrupt changes in sedimentation such as that seen in core 1 are to be expected.

Environmental record

A third alternative for the origin of the swamp is climatic change. The basal sediment is composed of alluvium transported by the Loboï River (S) at core 1 and the Kapkuikui River at core 7. High magnetic susceptibility (550–700 SI) of the alluvium at core 7 reflects the coarse mineral detritus (sand) derived from the freshly weathered trachyphonolites of the Bogoria Plateau (Fig. 2B). Lower magnetic susceptibility (< 200 SI) of basal sediments in core 1 results from the presence of more extensively weathered silts and clay. These fine-grained sediments were deposited on the distal floodplain of the Loboï River (S) (Fig. 4) with a likely addition of wind-blown sediment. Siderite bands and finely disseminated siderite nodules in the alluvium (Fig. 7) record Fe-reducing conditions that developed as the surface was gradually submerged. Evidence for periodic emergence of the upper peat interval at core 1 is found by the presence of jarosite, which commonly results from the oxidation of early diagenetic pyrite that originally formed during periods of submergence.

The poorly drained alluvial surface at ≈ 700 BP ultimately developed into a large lush wetland (3–4 km²) that supported a variety of wetland plants. The wetland record (organic-rich clays and peat) thins from 1 m in the south to a few centimetres at the northern terminus. The lithological record fines upwards and becomes more organic rich: LOI ranges from $\approx 5\%$ to 40% in the peat. The mineral matter deposited in the spring-fed wetland was probably transported by wind. Dating suggests that the sedimentation rate in the wetland sediments is relatively low (≈ 1.0 mm \cdot year⁻¹).

The preservation potential of groundwater-fed wetlands in rift settings will be greatest on valley floors adjacent to normal faults. The organic-rich record is less likely to be weathered in areas undergoing subsidence. Furthermore, such wetlands are commonly fed and maintained by fault-line springs. Unlike wetlands fed by surface waters, riverine marsh or high water tables, groundwater recharge from fault-line springs may continue even during dry periods when the land surface undergoes aridification (cf. Renaut & Jones, 1997, their fig. 5). Consequently, the

wetland and its lithological sedimentary record has reasonably high preservation potential, and its biological record (e.g. changes in macrophytes, aerial pollen record, diatoms) may record both local and regional environmental changes. Palaeowetland deposits are usually fine grained with mineralogy reflecting reducing conditions (or alternating oxidizing–reducing conditions on the wetland margin) and characterized by the presence of diatoms, wetland pollen and possibly plant remains.

Palaeoclimate record

The pedological record revealed an abrupt shift from predominantly C4 vegetation to C3 vegetation with the initiation of the wetland (Driese *et al.*, 2004). Minor fluctuations in climate (wet/dry periods) are recorded in the soil pit at the edge of Loboï Swamp, indicating that at least the periphery has dried out repeatedly in the past. Confirmation for periodic drying includes clay illuviation features and shrinkage cracks observed in soil thin sections (Driese *et al.*, 2004). Evidence for soil saturation includes redoximorphic features (Fe reduction and precipitation of siderite and pyrite) and preservation of abundant organic matter. Evidence for substantial aeolian dust-flux additions during pedogenesis include net additions of Zr (probably as zircon silt grains) and of Na, K, Al and Si (as clays) to the wetland soil, compared with the buried floodplain soil (Driese *et al.*, 2004). Although the Loboï wetland soil formed during a period of general aridification, it still records dramatic hydrological fluctuations (wet/dry periods), probably on a number of timescales ranging from annual (monsoonal) to decadal (climatic oscillations such as El Niño/La Niña) or perhaps longer (Fig. 3).

The pollen record provides additional information on palaeoclimate. The high grass (Poaceae) percentages suggest open vegetation, characteristic of drier environments, although bush may have been an important component of the vegetative cover. Drier conditions are supported by the relatively high percentages of montane taxa, which indicate unimpeded long-distance dispersal from wetter highland regions. The Poaceae count from modern Lake Bogoria bottom-sediment samples is about half that recorded in zone 1 ($\approx 36\%$; Vincens, 1986; Vincens *et al.*, 1986). Other indications of drier climate are the low percentages of wetland-type taxa (*Typha* and *Cyperaceae*), suggesting that the Loboï wetland may have been less extensive than today. Other

research from Kenya supports the interpretation of a drier environment for the zone 1 timeframe. For example, Mohammed *et al.* (1995), working at Lake Turkana (Fig. 1), interpreted the pollen record as reflecting lower lake levels at that time. Verschuren (2001) and Verschuren *et al.* (2000) reported a prolonged saline lowstand for Lake Naivasha between 1000 and 680 BP (coeval with the Medieval Warm Period in Europe).

Overall, zone 2 indicates slightly wetter local conditions; this may be due to changes in the local hydrology of the Loboï Plain and/or to a wider regional climatic change. Verschuren *et al.* (2000) determined overall wetter conditions at Lake Naivasha coinciding with the Little Ice Age (≈ 700 –150 BP), punctuated, however, by three periods of severe aridity. It is interesting to note in the Loboï Swamp pollen record that the relative importance of Amaranthaceae (including Chenopodiaceae), generally low throughout zone 2 ($\approx 2\%$), more than doubles between levels 79–95 cm and 30–45 cm. Plants that produce Amaranthaceae pollen type indicate more saline conditions and, hence, could be associated with the increased soil salinity that was caused by evaporation during dry phases.

Subzone 2a is notable because the pollen indicates increasing human disturbance within the Loboï region. For example, *Rumex* is a weed associated with soil disturbance, and *Zea mays* (corn) is a food staple introduced in historically recent times. There is a rise in *Juniperus/Cupressus* in subzone 2a similar to that found by Lamb *et al.* (2003) in the palaeoecology record for the last century at Lake Naivasha. Subzone 2a therefore reflects increased human activity around the swamp.

The diatom record (core 1) also suggests an abrupt change in hydrology. In the lower part of the record, diatoms are scarce and mostly frustule fragments. This evidence is consistent with a floodplain setting, with a reworked flora that was probably derived from either swampy or riverine environments. The appearance of abundant diatoms in the record at 110–112 cm probably represents the initiation of a local wetland. There is a dramatic shift in the palaeoenvironment at 105 cm, with the development of a varied and common diatom flora that implies permanent swamp conditions. This sudden shift indicates a major hydrological change at the core site that could relate to river migration, abrupt climate change or be caused by increased inputs of groundwater related to contemporary fault movements. River migration is least likely as the record

is consistent to modern times and is presently not sourced by river water. The diatom record contains species that are commonly associated with groundwater-fed environments (hot springs and rivers partly fed by thermal springs) (Cholnoky, 1968; Gasse *et al.*, 1983).

Most diatom taxa in core 1 occur in a wide range of modern freshwater wetland settings in the Baringo–Bogoria area, including *Typha domingensis* and *Cyperus papyrus* swamps, marshes, streams and hot and cold springs. Diatom-inferred pH, conductivity and temperature based on calibration with modern samples from the Bogoria area (Owen *et al.*, 2004) suggest broad stability in these parameters (Fig. 10). Variability in flora probably reflects changes in type and density of swamp vegetation, and perhaps flow velocity and water depth. For example, *D. subovalis* and *R. gibberula* are often co-dominant in areas of stagnant water (or wet ground) with a relatively dense reed or grass cover. *R. gibberula* also occurs in hot springs and fluvial environments, but in lower numbers, and generally without *D. subovalis*. In contrast, *N. amphibia* and *N. kuetzingiana* are found in a wider range of modern settings, but mostly open, slightly deeper water littoral, swamp or fluvial environments. Core horizons with a higher proportion of *Nitzschia* (e.g. 55–40 cm) may therefore represent deeper water conditions than those indicated by the *Rhopalodia–Diploneis* flora, and perhaps flowing water (Gasse *et al.*, 1983; Gasse & Ceyve, 1987). The overall increase in *R. gibberula* and decline in *Nitzschia* in the top section of the core (pollen subzone 2a) may thus reflect a change, as macrophyte and clastic debris accumulated, from a shallow-water swamp to an area characterized by wet, but more solid ground.

The pollen record shows a shift to wetter conditions at ≈ 700 BP consistent with other high-resolution palaeoclimate studies in the area (Mohammed *et al.*, 1995; Verschuren *et al.*, 2000). The diatom record begins at ≈ 700 BP consistent with a fairly abrupt shift to wetter conditions. Higher rainfall would have increased recharge to the local aquifer and increased groundwater discharge to low areas, along fractures and to springs. However, the geometry of the wetland sediments (a wedge thickening towards the bounding faulted bedrock) suggests that subsidence may have played a role in providing accommodation space and preserving the organic record in this otherwise semi-arid environment.

The modern wetland

The composition of the shallow groundwater discharging into the wetland at the major springs is dominated by Na^+ , HCO_3^- (and minor Ca^{2+}), as a result of weathering of intermediate volcanic rocks in the area (Hover *et al.*, 2002). The similarity to the chemical composition of the Lobo River implies that the latter may be partly composed of a groundwater component. The elevated pH of 8.3 of swamp water relative to the groundwater pH of ≈ 6.4 – 6.8 is probably the result of degassing of dissolved CO_2 . The composition of water draining from the Lobo Swamp is similar to that of influent spring water, but the outflow is markedly depleted in DO (only $\approx 4\%$ saturated compared with $\approx 60\%$ for the springs). This is probably a result of DO consumption during aerobic decay of organic matter. Marsh surface waters collected within the vegetated areas at the coring sites range in DO saturation from $\approx 1\%$ at core 7 to 4% at core 1, supporting the idea of DO consumption during organic matter decay.

The slight increase in total alkalinity of marsh surface and effluent waters relative to influent spring waters (Table 2) is consistent with the input of dissolved CO_2 resulting from organic matter decay. The TDS of surface water at core 7 (1.53 g L^{-1}) is greater than that at core 1 (0.65) and may be the result of evapoconcentration because this site is distal from spring inflow.

The modern Lobo Swamp has two main vegetation zones: *Typha* dominated and *Cyperus papyrus* dominated (Table 1). *Typha* and associated species are rooted on ground that has fluctuating water levels (periodic submergence or drying), and the papyrus is a rhizomatous perennial plant that forms floating mats and requires permanently flooded areas to thrive. Water depth and its persistence throughout the year vs. seasonal drying controls the zonation and composition of the plants in the papyrus and *Typha* zones. Water-level fluctuations, in particular, have been shown to be among the important factors influencing plant distribution in wetlands (Keddy & Fraser, 2000). Seedlings of trees such as *Acacia* are found on the edges of the *Typha* zone, but no mature trees are found in this zone, indicating that tree seedlings may not survive periodic flooding.

Water-quality parameters associated with the *Typha* and papyrus zones show little variation (Table 2) and do not appear to influence plant distribution in the swamp. A narrow belt on the margin of the wetland (a fringe zone that is

subjected to frequent wet/dry periods) contains more salt-tolerant species, such as *Sporobolus spicatus*.

The swamp is currently under environmental stress. Comparison of the limits of the Lobo Swamp between 1969 (aerial photographs) and 2002 reveals a dramatic reduction of about 60% (Fig. 2B). This is presumably due mainly to siphoning of Lobo Swamp water for irrigation by a ditch dug in 1970 (Fig. 4). Although the effluent discharge in the irrigation ditch (0.035 m s^{-1}) draining the swamp is only 10% of spring influent discharge (0.35 m s^{-1}), the wetland water budget is probably negative given that water loss by evapotranspiration exceeds local precipitation by a factor of four. Without change in the current hydrological budget, the swamp is likely to continue to decrease in size. The recent avulsion of the Lobo River (Harper *et al.*, 2003) can only accelerate the process.

Lobo Swamp is part of the catchment of Lake Baringo. In recent years, the volume of water in Lake Baringo has fluctuated widely, and the lake was reduced substantially during a recent drought (Johansson & Svensson, 2002). The Lobo Swamp serves as a permanent freshwater source for animals and people and for maintaining biodiversity in the region (Homewood & Lewis, 1987). During the dry season (Fig. 3A), the *Typha* zone is their main source of fodder, and herds from the surrounding community depend on the resource. To promote growth of fresh fodder and to control cattle ticks, the swamp is routinely burned towards the end of the dry season. *Papyrus* stems are cut by local people for thatching roofs and mat making, putting additional pressure on the wetland ecology.

CONCLUSIONS

The Lobo Swamp area was a poorly drained floodplain environment during the late Holocene until ≈ 700 BP when it developed into a large wetland (3 – 4 km^2) that supported a variety of wetland plants. It has now shrunk to 1.5 km^2 . The sedimentological and biological records do not allow the equivocal determination of whether the initiation of the swamp was related to climate or tectonic subsidence. Climate change may have induced swamp development, but the location is tectonically controlled. Other studies in the rift suggest that climate was drier during the Medieval Warm Period (≈ 1000 – 700 BP) (Mohammed *et al.*, 1995) and that it subsequently became

slightly wetter, albeit with episodes of drier climate, during the Little Ice Age (\approx 730–150 BP) (Verschuren *et al.*, 2000; Verschuren, 2001). This is consistent with the findings from this study. However, the abrupt change in both pollen and diatom species (Figs 9 and 10), as well as the juxtaposition of the wetland to a fault (Fig. 4) and the general thinning of the wetland sediments away from the fault, strongly suggest that tectonics played some role. Tectonic subsidence would have provided accommodation space and lowered the surface near or at the water table. However, the coincidence of the development and growth of the Lobo wetland in synch with the regional climate shift to wetter conditions strongly suggests that climate played a major role.

Lobo Swamp is composed of rooted *Typha* (80%) and floating *Cyperus papyrus* (20%). The papyrus plants occur in areas of standing water (largely sourced by springs), and the *Typha* occur on relatively higher ground subject to changes in hydrological budget. The mean sedimentation rate over the last 700 years has been \approx 1 mm year⁻¹ with mineral matter being transported to the wetland in part by wind. The top of the pollen record reveals the addition of corn pollen and some weedy species associated with land use changes reflecting increased human activity and the change from pastoral lifestyles to agriculture systems. The wetland area has been subjected to an alarming decrease (\approx 60%) in size since 1969. This shrinking appears to be anthropogenic due to the utilization of swamp water for irrigation and avulsion of fluvial inflow. Under present hydrological conditions, the wetland is likely to continue to decrease in area.

ACKNOWLEDGEMENTS

Research was carried out under a permit (MOEST 13/001/32C 57/4) from the Ministry of Education, Science and Technology of Kenya, A.G. Kaaria, Senior Assistant Secretary, and was supported by NSF/EAR-0207705 to G. M. Ashley and V. C. Hover, Rutgers University, and NSF/EAR-0074745 to M. F. Goman, Cornell University; NSERC-GP000626 to R. W. Renaut, University of Saskatchewan; R. B. Owen received support from the Hong Kong Baptist University (FRG/00-01/I-44). Acknowledgement is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society for partial support of this research (PRF 36498-AC8, Hover).

Rutgers University-New Brunswick also provided funds. We are grateful to Dr Karega-Munene, Director of Archaeology, and National Museums of Kenya (NMK) for assistance with research logistics. We are especially grateful to William Kimosop, Senior Warden for the Lake Bogoria National Reserve, and Maushe Kidundo (World Wildlife Fund) for their encouragement of the research. We appreciate the expertise of naturalist Michael Kimeli and discussions with Musa Cheruiyot and Fabian Musila, Lake Bogoria Community Based Wetlands Project. We would particularly like to thank Veronica Muiruri, Paleobotany Department, NMK, who provided able assistance with pollen preparation and identification. The cation and anion analyses of water samples were kindly provided by Dr A. M. Martini, Luce Environmental Geochemistry Laboratory, Amherst College. Richard F. Bopp, Rensselaer Polytechnic Institute conducted the Pb²¹⁰ analyses.

REFERENCES

- Ambraseys, N.N. (1991) Earthquake hazard in the Kenya Rift: the Subukia earthquake 1928. *Geophys. J. Int.*, **105**, 253–269.
- Appleby, P.G. and Oldfield, F. (1978) The calculation of lead-210 dates assuming constant supply of unsupported ²¹⁰Pb to the sediments. *Catena*, **5**, 1–8.
- Ashley, G.M. (2001) Orbital rhythms, monsoons, and playa lake response, Olduvai basin, Equatorial East Africa at 1.85–1.75 Ma. *EOS, Trans. Am. Geophys. Union*, **82**, F759.
- Ashley, G.M., Driese, S.G., Maitima Mworira, J., Muasya, A.M., Hover, V.C., Owen, R.B. and Goman, M.F. (2002a) The evolution of a freshwater wetland in a semi-arid environment, Lobo Swamp, Kenya, East Africa. *EOS, Trans. Am. Geophys. Union*, **83**, F899.
- Ashley, G.M., Goman, M., Hover, V.C., Owen, R.B., Renaut, R.W. and Muasya, A.M. (2002b) Artesian blister wetlands, a perennial water resource in the semi-arid rift valley of East Africa. *Wetlands*, **22**, 686–695.
- Atmaoui, N. and Hollnack, D. (2003) Neotectonics and extension direction of the Southern Kenya Rift, Lake Magadi area. *Tectonophysics*, **364**, 71–83.
- Birks, H.J.B. and Birks, H.H. (1980) *Quaternary Palaeoecology*. University Park Press, Baltimore, MD, 299 pp.
- Appel, M.A. and Molnar, P. (2001) Closing of the Indonesian seaway as a precursor to East African aridification around 3–4 million years ago. *Nature*, **411**, 157–162.
- Cerling, T., Wang, Y. and Quade, J. (1993) Expansion of C4 ecosystems as an indicator of global ecological change in the late Miocene. *Nature*, **361**, 344–345.
- Cholnoky, B.J. (1968) *Die Okologie der Diatomeen in Binnengewässern*. Cramer, Lehre, Germany.
- Crafter, S.A., Njuguna, S.G. and Howard, G.W. (eds) (1992) *Wetlands of Kenya*. IUCN, Gland, Switzerland, 183 pp.
- deMenocal, P. (1995) Plio-Pleistocene African climate. *Science*, **270**, 53–59.
- Deocampo, D.M. (2002) Sedimentary processes and lithofacies in lake-margin groundwater-fed wetlands in East Africa. In:

- Sedimentation in Continental Rifts* (Eds R.W. Renaut and G.M. Ashley), *SEPM Spec. Publ.*, **72**, 295–308.
- Driese, S.G., Ashley, G.M., Li, Z.-H., Hover, V.C. and Owen, R.B.** (2004) Possible Late Holocene equatorial palaeoclimate record based upon soils spanning the Medieval Warm Period and Little Ice Age, Lobo Plain, Kenya. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, in press.
- Faegri, K. and Iversen, J.** (1989) *Textbook of Pollen Analysis*. J. Wiley & Sons, New York.
- Farrand, W.R., Redding, R.W., Wolpoff, M.H. and Wright, H.T.** (1976) *An Archeological Investigation on the Lobo Plain, Baringo District, Kenya*. Technical Report. Museum of Anthropology, University of Michigan, 4.
- Gasse, F.** (1986) East Africa diatoms: taxonomy, ecological distribution. *Bibl. Diatomol.*, **11**, 201.
- Gasse, F.** (1987) Diatoms for reconstructing paleoenvironments and paleohydrology in tropical semi-arid zones. *Hydrobiologia*, **154**, 127–163.
- Gasse, F. and Ceyve, C.** (1987) Les diatomées et l'évolution des milieux en termes hydrologiques. In: *Le Demi-Graben de Baringo-Bogoria, Rift Gregory, Kenya* (Eds J.J. Tiercelin and A. Vincens), *Bull. Centres Rech. Explor.-Prod. Elf-Aquitaine*, **11**, 414–425.
- Gasse, F., Talling, J.F. and Kilham, P.** (1983) Diatom assemblages in East Africa: classification, distribution and ecology. *Rev. Hydrobiol. Trop.*, **16**, 3–34.
- Griffiths, P.W.** (1977) *Geology of the Lake Hannington-Perkerra River area, Kenya Rift Valley*. Unpubl. PhD Thesis, University of London, 187 pp.
- Griffiths, P.W. and Gibson, I.L.** (1980) The geology and petrology of the Hannington Trachyphonolite formation, Kenya Rift Valley. *Lithos*, **13**, 43–53.
- Hamilton, A. and Taylor, D.** (1986) Mire sedimentation in East Africa. In: *Sedimentation in the African Rifts* (Eds L.R. Frostick, R.W. Renaut, I. Reid and J.J. Tiercelin), *Geol. Soc. Spec. Publ.*, **25**, 211–217.
- Harper, D.M., Brooks Childress, R., Harper, M.M., Boar, R.R., Hickey, P., Mills, S.C., Otieno, N., Drane, T., Vareschi, E., Nasirwa, O., Mwatha, W.E., Darlington, J.P.E.C. and Escuté-Gasulla, X.** (2003) Aquatic biodiversity and saline lakes: Lake Bogoria National Reserve, Kenya. *Hydrobiologia*, **500**, 259–276.
- Hautot, S., Tarits, P., Whaler, K., Le Gall, B., Tiercelin, J.J. and Le Turdu, C.** (2000) Deep structure of the Baringo rift basin (central Kenya) from three-dimensional magnetotelluric imaging: implications for rift evolution. *J. Geophys. Res. B, Solid Earth Planets*, **105**, 23493–23518.
- Heiri, O., Lotter, A.F. and Lemcke, G.** (2001) Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *J. Paleolimnol.*, **25**, 101–110.
- Hill, A.** (2002) Paleoanthropological research in the Tugen Hills, Kenya. *J. Human Evol.*, **42**, 1–10.
- Homewood, K. and Lewis, J.** (1987) Impact of drought on pastoral livestock in Baringo, Kenya 1983–85. *J. Appl. Ecol.*, **24**, 615–631.
- Hover, V.C., Ashley, G.M. and Renaut, R.W.** (2002) Geochemical fingerprints of waters in the Lake Baringo-Bogoria region, Kenya: Implications for hydrogeochemical processes and water quality. *EOS, Trans. Am. Geophys. Union, Fall Meeting Suppl.* **83**, Session H-40 (Water Quality of Natural Systems), Abstract H61C-0803.
- Hughes, R.H. and Hughes, J.S.** (1992) *A Directory of African wetlands*. IUCN, Gland/UNEP, Nairobi/WCMC, Cambridge, 820 pp.
- Johansson, J. and Svensson, J.** (2002) *Land Degradation in the Semi-arid Catchment of Lake Baringo, Kenya*. Project Report no. B343. Earth Sciences Centre, Göteborg University, Göteborg, 79 pp.
- Jones, M.B. and Milburn, R.R.** (1978) Photosynthesis characteristics of papyrus (*Cyperus papyrus* L.). *Photosynthetica*, **12**, 197–199.
- Keddy, P. and Fraser, L.H.** (2000) Four general principles for the management and conservation of wetlands in large lakes: the role of water levels, nutrients, competitive hierarchies and centrifugal organization. *Lakes Reservoirs: Res. Man.*, **5**, 177–185.
- Lamb, H., Darbyshire, I. and Verschuren, D.** (2003) Vegetation response to rainfall variation and human impact in central Kenya during the past 1100 years. *Holocene*, **13**, 285–292.
- LaVigne, M. and Ashley, G.M.** (2001) *Climatology and Rainfall Patterns: Lake Bogoria National Reserve (1976–2001)*. Department of Geological Sciences, Rutgers University, Piscataway, NJ, 48 pp.
- Le Turdu, C., Tiercelin, J.J., Coussement, C.J., Rolet, J., Renaut, R.W., Richert, J.P., Xavier, J.P. and Coquelet, D.** (1995) Basin structure and depositional patterns interpreted using a 3D remote sensing approach: the Baringo-Bogoria basins, central Kenya Rift, East Africa. *Bull. Centres Rech. Explor.-Prod. Elf Aquitaine*, **19**, 1–37.
- Le Turdu, C., Tiercelin, J.J., Richert, J.P., Rolet, J., Xavier, J.-P., Renaut, R.W., Lezzar, K. and Coussement, C.** (1999) Influence of preexisting oblique discontinuities on the geometry and evolution of extensional fault patterns: evidence from the Kenya Rift using SPOT imagery. In: *Geoscience of Rift Systems – Evolution of East Africa* (Ed. C.K. Morley), *AAPG Studies Geol.*, **44**, 173–191.
- Liutkus, C.M. and Ashley, G.M.** (2003) Facies model of a semi-arid freshwater wetland, Olduvai Gorge, Tanzania. *J. Sed. Res.*, **73**, 691–705.
- McCall, G.J.H.** (1967) Geology of the Nakuru-Thomson's Falls, Lake Hannington area. *Rep. Geol. Surv. Kenya*, **78**, 122 pp.
- Mitsch, W.J. and Gosselink, J.G.** (2000) *Wetlands*, 3rd edn. John Wiley & Sons, New York, 920 pp.
- Mohammed, M.U., Bonnefille, R. and Johnson, T.C.** (1995) Pollen and isotopic records in Late Holocene sediments from Lake Turkana, Kenya. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **119**, 371–383.
- Muasya, A.M., Hover, V.C., Ashley, G.M., Owen, R.B., Goman, M.F. and Kimeli, M.** (2004) Diversity and distribution of macrophytes in a freshwater wetland, Lobo Swamp (Rift Valley) Kenya. *J. East Afr. Nat. Hist. Soc.*, in press.
- Mwasi, B.** (2001) Land use conflicts resolution in a fragile ecosystem using multi-criteria evaluation (MCE) and a GIS-based decision support system (DSS). In: *Proceedings of an International Conference on Spatial Information for Sustainable Development*, Nairobi, Kenya. Section TS14.2, pp. 1–11.
- Owen, R.B., Renaut, R.W., Hover, V.C., Ashley, G.M. and Muasya, A.M.** (2004) Swamps, springs, and diatoms: wetlands regions of the semi-arid Bogoria-Baringo Rift, Kenya. *Hydrobiologia*, **518**, 59–78.
- Potts, R.** (1996) Evolution and climate variability. *Science*, **273**, 922–923.
- Renaut, R.W.** (1982) *Late Quaternary geology of the Lake Bogoria fault-trough, Kenya Rift Valley*. Unpubl. PhD Thesis, University of London, 498 pp.
- Renaut, R.W.** (1993) Zeolitic diagenesis of late Quaternary fluviolacustrine sediments and associated calcrete formation in the Lake Bogoria basin, Kenya Rift Valley. *Sedimentology*, **40**, 271–301.

- Renaut, R.W. and Jones, B. (1997) Controls on aragonite and calcite precipitation in hot spring travertines at Chemurkeu, Lake Bogoria, Kenya. *Can. J. Earth. Sci.*, **34**, 810–818.
- Renaut, R.W. and Jones, B. (2000) Microbial precipitates around continental hot springs and geysers. In: *Microbial Sediments* (Eds R. Riding and S. Awramik), pp. 187–195. Springer, Berlin.
- Renaut, R.W. and Owen, R.B. (1987) Les 'Silts de Loboi'. In: *Le Demi-Graben de Baringo-Bogoria, Rift Gregory, Kenya. 30000 Ans d'Histoire Hydrologique et Sédimentaire* (Eds J.J. Tiercelin and A. Vincens), *Bull. Centres Rech. Explor.-Prod. Elf-Aquitaine*, **11**, 502–505.
- Renaut, R.W. and Tiercelin, J.J. (1994) Lake Bogoria, Kenya Rift Valley – a sedimentological overview. In: *Sedimentology and Geochemistry of Modern and Ancient Saline Lakes* (Eds R.W. Renaut and W.M. Last), *SEPM Spec. Publ.*, **50**, 101–123.
- Renaut, R.W., Tiercelin, J.J. and Owen, R.B. (2000) Lake Baringo, Kenya Rift Valley, and its Pleistocene precursors. In: *Lake Basins Through Space and Time* (Eds E. Gierlowski-Kordesch and K. Kelts), *AAPG Stud. Geol.*, **46**, 561–568.
- Rooney, D. and Hutton, V.R.S. (1977) A magnetotelluric and magnetovariational study of the Gregory Rift Valley, Kenya. *Geophys. J. Roy. Astronom. Soc.*, **51**, 91–119.
- Rosen, M.R. (1994) The importance of groundwater in playas: a review of playa classification and the sedimentology and hydrology of playas. In: *Paleoclimate and Basin Evolution of Playa Systems*. (Ed. M.R. Rosen), *GSA Spec. Paper*, **289**, 1–18.
- Rosendahl, B.R. (1987) Architecture of continental rifts with special references to East Africa. *Annu. Rev. Earth Planet. Sci.*, **15**, 445–503.
- Rounds (2003) Alkalinity calculator. <http://oregon.usgs.gov/alk/>. Last accessed June 2003.
- Rowntree, K.M. (1989) Rainfall characteristics, rainfall reliability and the definition of drought: Baringo District, Kenya. *South Afr. Geogr. J.*, **71**, 74–80.
- Snelder, D.J. and Bryan, R.B. (1995) The use of rainfall simulation tests to assess the influence of vegetation density on soil loss in degraded rangelands in the Baringo District, Kenya. *Catena*, **25**, 105–116.
- Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Dromer, B., McCormac, G., van der Plicht, J. and Spurk, M. (1998) INTCAL98 radiocarbon age calibration, 24,000–0 cal BP. *Radiocarbon*, **40**, 1041–1083.
- Thenya, T. (2001) Challenges of conservation of dryland shallow waters, Ewaso Narok Swamp, Laikipia District wetlands, Kenya. *Hydrobiologia*, **458**, 121–130.
- Thom, D.J. and Martin, N.L. (1983) Ecology and production in Baringo-Kerio Valley, Kenya. *Geogr. Rev.*, **73**, 15–29.
- Thompson, K. and Hamilton, A.C. (1983) Peatlands and swamps of the African continent. In: *Ecosystems of the World, Mires: Swamp, Bog, Fen and Moor, Regional Studies* (Ed. A.J.P. Gore), pp. 331–373. Elsevier, Amsterdam, The Netherlands.
- Tiercelin, J.J. (1990) Rift-basin sedimentation: responses to climate, tectonism and volcanism. Examples of the East African Rift. *J. Afr. Earth Sci.*, **10**, 283–305.
- Tiercelin, J.J. and Vincens, A. (eds) (1987) Le demi-graben de Baringo-Bogoria, Rift Gregory, Kenya. 30000 ans d'histoire hydrologique et sédimentaire. *Bull. Centres Rech. Explor.-Prod. Elf-Aquitaine*, **11**, 249–540.
- Tiercelin, J.J., Perinet, G., Le Fournier, J., Bieda, S. and Robert, P. (1982) Lacs du rift est-africain, exemples de transition eaux douces–eaux salées: le lac Bogoria, rift Gregory, Kenya. *Soc. Géol. Fr. Mém.*, **NS**, **144**, 217–230.
- Tongue, J., Maguire, P. and Burton, P. (1994) An earthquake study in the Lake Baringo basin of the central Kenya Rift. *Tectonophysics*, **236**, 151–164.
- Trauth, M.H., Deino, A.L., Bergner, A.G.N. and Strecker, M.R. (2003) East African climate change and orbital forcing during the last 175 kyr BP. *Earth Planet. Sci. Lett.*, **206**, 297–313.
- Verschuren, D. (2001) Reconstructing fluctuations of a shallow East African lake during the past 1800 years from sediment stratigraphy in a submerged crate basin. *J. Paleolimnol.*, **25**, 297–311.
- Verschuren, D., Laird, K.R. and Cumming, B.F. (2000) Rainfall and drought in equatorial east Africa during the past 1,100 years. *Nature*, **403**, 410–414.
- Vincens, A. (1986) Diagramme pollinique d'un sondage pléistocène supérieur-Holocène du lac Bogoria (Kenya). *Rev. Palaeobot. Palytol.*, **47**, 169–192.
- Vincens, A., Casanova, J. and Tiercelin, J.J. (1986) Palaeolimnology of Lake Bogoria (Kenya) during the 4500 BP high lacustrine phase. In: *Sedimentation in the African Rifts* (Eds L.E. Frostick, R.W. Renaut, I. Reid and J.J. Tiercelin), *Geol. Soc. Spec. Publ.*, **25**, 323–330.
- Von Hohnel, L. (1891) *Discovery of Lakes Rudolf and Stefanie*. Longmans, London.
- Vrba, E.S. (1995) The fossil record of African antelopes (Mammalia, Bovidae) in relation to human evolution and paleoclimate. In: *Paleoclimate and Evolution, with Emphasis on Human Origins* (Eds E.S. Vrba, G.H. Denton, T.C. Partridge and L.H. Burckle), pp. 354–424. Yale University Press, New Haven, CT.
- Young, P.A.V., Maguire, P.K.H., Laffoley, N.d'A. and Evans, J.R. (1991) Implications of the distribution of seismicity near Lake Bogoria in the Kenya Rift. *Geophys. J. Int.*, **105**, 665–674.

Manuscript received 17 June 2003; revision accepted 5 May 2004.

