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Tectonic and climatic control on evolution of rift lakes in the Central Kenya Rift, East Africa

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ABSTRACT

The long-term histories of the neighboring Nakuru–Elmenteita and Naivasha lake basins in the Central Kenya Rift illustrate the relative importance of tectonic versus climatic effects on rift-lake evolution and the formation of disparate sedimentary environments. Although modern climate conditions in the Central Kenya Rift are very similar for these basins, hydrology and hydrochemistry of present-day lakes Nakuru, Elmenteita and Naivasha contrast dramatically due to tectonically controlled differences in basin geometries, catchment size, and fluvial processes. In this study, we use eighteen ^{14}C and $^{40}Ar/^{39}Ar$ dated fluvio-lacustrine sedimentary sections to unravel the spatiotemporal evolution of the lake basins in response to tectonic and climatic influences. We reconstruct paleoclimatic and ecological trends recorded in these basins based on fossil diatom assemblages and geologic field mapping. Our study shows a tendency towards increasing alkalinity and shrinkage of water bodies in both lake basins during the last million years. Ongoing volcano-tectonic segmentation of the lake basins, as well as reorganization of upstream drainage networks have led to contrasting hydrologic regimes with adjacent alkaline and freshwater conditions. During extreme wet periods in the past, such as during the early Holocene climate optimum, lake levels were high and all basins evolved toward freshwater systems. During drier periods some of these lakes revert back to alkaline conditions, while others maintain freshwater characteristics. Our results have important implications for the use and interpretation of lake sediment as climate archives in tectonically active regions and emphasize the need to deconvolve lacustrine records with respect to tectonics versus climatic forcing mechanisms.

1. Introduction

The East African Rift System (EARS) is a first-order tectonic and topographic feature in East Africa, extending for over more than 5000 km from the Gulf of Aden to Mozambique (Fig. 1). This rift system hosts a variety of fluvio-lacustrine basins of different sizes, where sedimentary environments are profoundly influenced by tectonic, volcanic and climate-driven processes (cf., Tiercelin and Lezzar, 2002). During the last 45 million years, extensional tectonics with rift-shoulder uplift and associated volcanism has created a complex patchwork of faulted mountain ranges and sedimentary basins (Baker et al., 1972; Ebinger et al., 2000; Macdonald et al., 2001; Tiercelin and Lezzar, 2002). After a Pleistocene change in extension direction from ENE–WSW to NW–SE, internal rift segmentation and the continued formation of volcanic edifices has resulted in the evolution of a series of distinct small-scale sedimentary basins nested in the larger rift basins. These young zones of extension display complex geometries and fault patterns and associated drainage networks, particularly in the eastern branch of the rift (cf., Strecker et al., 1990; Delvaux et al., 1998; Ring et al., 2005; Mortimer et al., 2007).

The uplift of the Ethiopian and Kenyan domes preceding rifting formed important orographic barriers in East Africa (Ebinger et al., 1993; Foster and Gleadow, 1996; Sepulchre et al., 2006; Pik et al., 2008). Superposed major global climate transitions at ~2.5, ~1.8 and 1.0 Ma ago placed East Africa into a highly sensitive, semi-arid to arid climate realm (Vrba et al., 1995; Tiercelin and Lezzar, 2002; DeMenocal, 2004; Trauth et al., 2005; Sepulchre et al., 2006; Ségalen et al., 2007). Consequently, sediments stored in the basins of the EARS should reflect both tectonic and climate forcing

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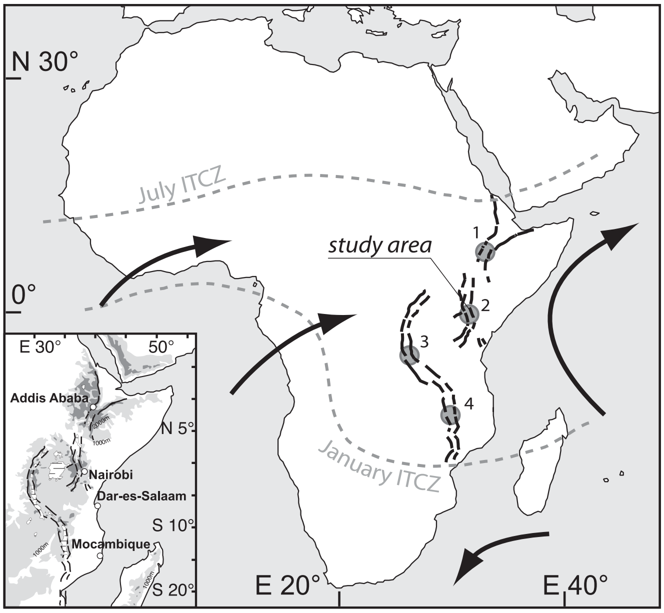


Fig. 1. Map of Africa showing the tectonic versus climatic framework of the study area. Location of the East African Rift System (EARS) and location of key sites of similar investigation: (1) Ethiopian Rift, (2) Northern, Central and Southern Kenya Rift, (3) Lake Tanganyika, (4) Lake Malawi. Climatic signatures are controlled by the migration of the Intertropical Convergence Zone (ITCZ; maximum positions of July and January indicated) and main airflow pattern (arrows). Insert shows topography of the EARS and main tectonic faults (cf. Fig. 2 and 3 for details).

mechanisms, and thus lend themselves to develop paleoclimatic, environmental and tectonic reconstructions.

Several investigations of sedimentary sequences exposed in the EARS have been undertaken, mainly with the emphasis to reconstruct the effects of late-Pleistocene to Holocene climate change (e.g., Butzer et al., 1969; Hecky and Kilham, 1973; Richardson and Dussinger, 1986; Gasse, 2000; Verschuren et al., 2000; Trauth et al., 2005; Scholz et al., 2007; Gasse et al., 2008). In these studies, it is generally assumed that the relative importance of tectonic versus climatic forcing on lake-level behavior diminishes from longer ($>10^5$ years) to shorter ($<10^4$ years) timescales. Although this interpretation may hold true for the large-scale patterns of the western branch of the EARS, volcano-tectonic processes on smaller temporal and spatial scales associated with the ongoing segmentation of rift basins may influence basin development in the eastern branch of the EARS on timescales of less then 100,000 years (Strecker et al., 1990; Roessner and Strecker, 1997; Delvaux et al., 1998; Le Turdu et al., 1999; Yuretich and Ervin, 2002). In the eastern branch of the EARS, tectonically controlled differences in basin geometries and drainage patterns have resulted in highly contrasting lake character and sedimentary environments, ranging from shallow and highly alkaline (e.g., Bogoria, Nakuru, Magadi, Natron) to freshwater environments (e.g., Naivasha and Baringo) or highly transient environments such as at Lake Logipi in the northern Kenya Rift. Lacustrine sedimentary sequences exposed in these basins should therefore be interpreted in the context of both, tectonic and climatic influences, particularly when these sediments are used for regional, or even global paleoclimate reconstructions.

In this study, we combine previously published data of Holocene to Pleistocene lake history in the Central Kenya Rift (CKR) (Richardson and Dussinger, 1986; Bergner and Trauth, 2004; Trauth et al., 2005; Dühnforth et al., 2006; Trauth et al., 2007) with new proxies of mid-Pleistocene paleolake evolution and new data from geologic field mapping of young tectonic fault systems. By comparing the ultimate one million years of hydrologic evolution of the neighboring Nakuru–Elmenteita and Naivasha lake basins, we assess the relative importance of climatic versus tectonic influences on sedimentologic–hydrologic regimes in a highly differential rift basin. We demonstrate that the paleoenvironmental characteristics of lake sediments, often interpreted as entirely climatically controlled, may be fundamentally influenced by tectonic processes. Our study emphasizes the need to reach a better understanding of volcano-tectonic processes and their impact on rift-basin differentiation combined with a reconstruction of climatic conditions in East Africa.

2. Setting

The Nakuru–Elmenteita and Naivasha basins lie in the center of the East African plateau at the highest elevation of any lake basins in the eastern branch of the EARS (Figs. 1 and 2). The tectonic and magmatic history of this part of the rift was initiated by the evolution of E dipping normal faults forming a halfgraben between 12 and 6 Ma BP (Baker et al., 1988). Between 5.5 and 3.7 Ma this halfgraben was antithetically faulted resulting in a full-graben morphology (Baker et al., 1988; Roessner and Strecker, 1997). The W dipping Sattima fault and the Aberdare volcanic complex (4000 m a.s.l.) border the CKR to the east, whereas the Mau Escarpment (3080 m) forms the western border (Baker and Wohlenberg, 1971; Baker et al., 1988). By 2.6 Ma, further tectonic activity created the 30-km-wide intra-rift Kinangop Plateau and the 40-km-wide inner rift depression (Baker et al., 1988; Strecker et al., 1990; Clarke et al., 1990) (Fig. 2). The inner rift was subsequently covered by trachytic, basaltic and rhyolitic lavas and tuffs and continues to be cut by normal faulting along the volcano-tectonic axis (McCall et al., 1967; Clarke et al., 1990; Strecker et al., 1990). A change in extension direction in mid-Pleistocene time subjected the pre-existing structures that constitute the overall geometry of the rift to oblique extension, which resulted in en échelon, NNE striking normal faults that are linked by complex transfer zones (Bosworth and Strecker, 1997). In addition, older faults were reactivated as obliquely slipping normal faults, and in some cases local strike-slip faults (Strecker et al., 1990; Bosworth and Strecker, 1997; Zielke and Strecker, 2009). The young structures of the inner rift are accompanied by late-Pleistocene to Holocene eruptive centers, such as Menengai (2278 m), Eburru (2840 m) and Longonot (2776 m), and smaller rhyolitic domes and basaltic lava flows, such as at Olkaria (2440 m) (Fig. 2). As a consequence, the present-day inner rift is compartmentalized into smaller basins that are bordered by normal faults and intervening volcanic edifices (Clarke et al., 1990).

Climatically, the CKR is situated between the influence of the trade-wind/monsoon circulation over the Indian Ocean and air masses from the Congo basin (Vincent et al., 1979; Bergner et al., 2003) (Figs. 1 and 2). Local precipitation predominantly arises from orographic rainfall on rift flanks (Rodhe and Virji, 1976; Vincent et al., 1979; Nicholson, 1996; Bergner et al., 2003). In contrast, the low relief and wind-stressed inner rift is characterized by high evaporation and reduced precipitation resulting from the orographic conditions and the direct transition of the Intertropical Convergence Zone (ITCZ). The intra-rift lakes Nakuru (1758 m a.s.l.), Elmenteita (1786 m), and Naivasha (1889 m) thus have a negative moisture budget and strongly depend on freshwater supply from upstream catchments (Milbrink, 1977; Gaudet and Melack, 1981; Åse, 1987; Verschuren, 1999; Becht and Harper, 2002) (Fig. 2). The characteristics of the fluvial network, including catchment size, drainage-network patterns, and basin shape, primarily control the hydrology of the modern CKR lakes. Generally, north–south to north–northwest–south–southeast striking fault-blocks bordering the inner rift to the east deflect most of the rivers draining the more

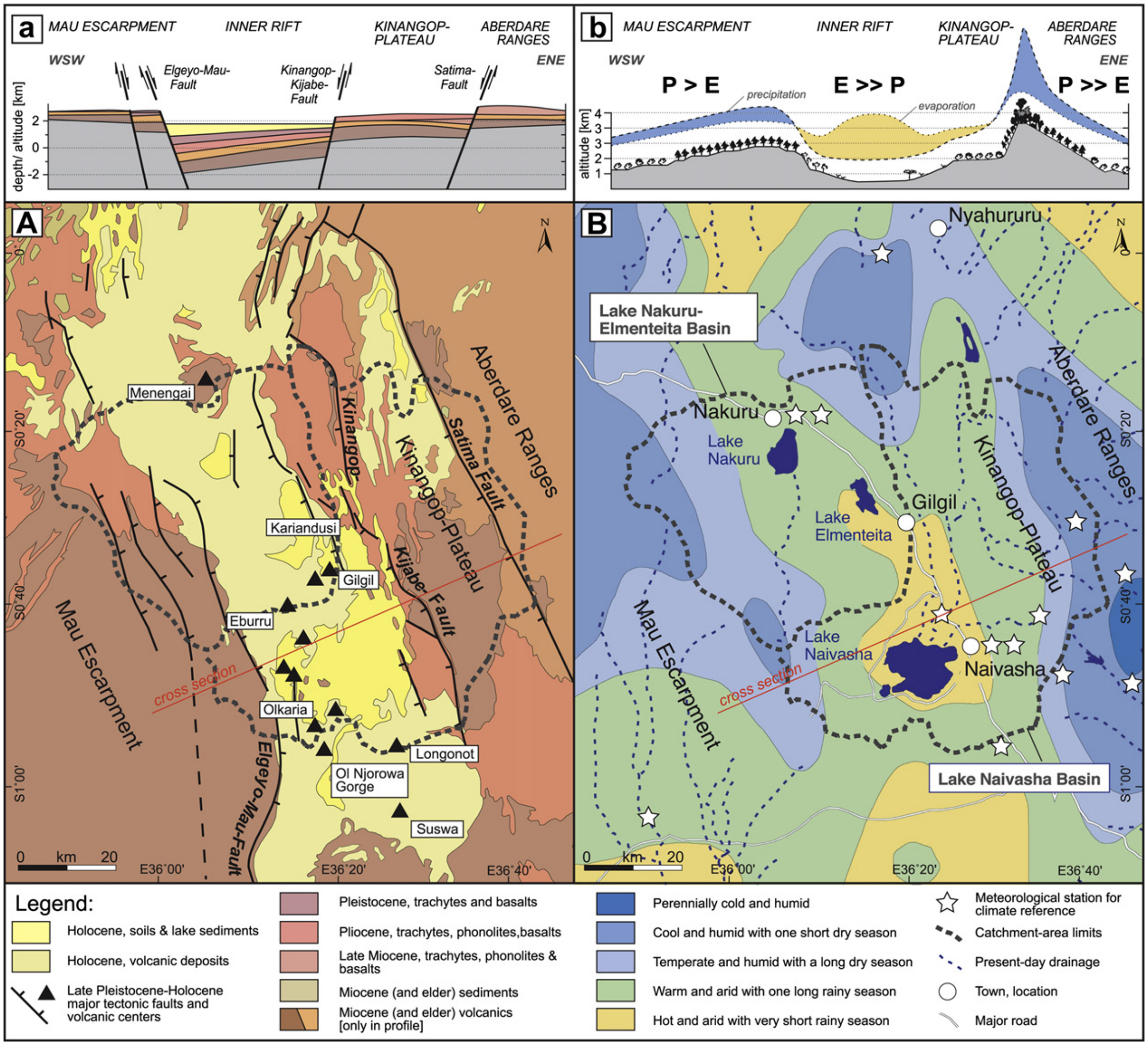


Fig. 2. Regional map of the Central Kenya Rift comparing present-day geologic–tectonic and hydro-climatic settings. The (A) geologic framework shows an NNW–SSE-aligned rift-system structure, with older volcanic units on the rift-shoulders versus younger edifies on the rift floor. A schematic profile (a) marks major antithetic faulting, separating the outer and inner rift since Miocene times. Geologic units after MERD (1987) and Clarke et al. (1990). The (B) hydro-climatic situation follows a similar NNW–SSE-aligned pattern and contrasting trend with humid rift-shoulders and more arid conditions on the rift floor. Generalized precipitation-evaporation patterns from Jätzold (1981) and meteorological stations (stars) (cf., Bergner et al., 2003; Dühnforth et al., 2006). The (b) schematic hydro-climatic profile (blue versus yellow shadings representing the spatial difference of precipitation-evaporation with data from 17 meteorological stations) overlaying idealized present-day topography (grey) illustrates high precipitation–evaporation (P–E) ratios on the Mau Escarpment and Aberdare Ranges, but P–E deficit on the rift floor. Note differences in size of catchment areas (in B), which lead to higher river discharge towards Naivasha compared to Nakuru–Elmenteita. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

humid Aberdare Ranges and the Kinangop Plateau towards the south into the Naivasha basin. In contrast, the Nakuru–Elmenteita basin receives only minor freshwater supply from small catchments in the inner rift and limited areas of the Kinangop Plateau. Consequently, the present-day Nakuru, Elmenteita and Naivasha lakes demonstrate significant differences in hydrology and hydrochemistry. For example, present-day Nakuru and Elmenteita lakes are highly alkaline, relatively small (40 and 24 km^2), and less than 2 m deep. Conversely, Lake Naivasha is a freshwater lake, which covers an area of $\sim$150 km^2 and is up to 9 m deep (Milbrink, 1977) (Fig. 3; Table 1).

Interestingly, the older history of the lakes, as reconstructed from ^{14}C-dated Holocene lake deposits, paleo-shorelines, and $^{40}Ar/^{39}Ar$ dating of tephra-bearing Pleistocene sedimentary sequences, indicates more extensive lakes and more uniform hydrologic conditions during distinct periods of climate-optimum conditions (Richardson and Dussinger, 1986; Verschuren et al., 2000; Bergner and Trauth, 2004; Trauth et al., 2005). At these times, the Naivasha and Nakuru-Elmenteita basins hosted lakes that were almost 200 m deep- and more than 650 km^2 in area extent (Bergner et al., 2003; Dühnforth et al., 2006) (Fig. 3; Table 1). Reconstruction from fossil diatoms reveals striking similarities in paleolake hydrochemistry in these environments (cf., Richardson and Dussinger, 1986; Trauth et al., 2005). The similar lake character and temporal coincidence of lake highstands with the timing of climate-optimum periods suggest that higher moisture levels in the course of intensified atmospheric convergence within the ITCZ were the most likely cause for higher lake levels in the CKR (Bergner and Trauth, 2004; Trauth et al., 2005; Dühnforth et al., 2006). The similarity of the paleolake characteristics dramatically contrasts with the modern conditions of these basins and is either intimately linked to climate controlled hydrologic separation of the lakes or a shift from a climate-dominated hydrologic regime toward the modern, tectonically and morphologically constrained system.

3. Methods

To separate tectonic and climatic influences on lake evolution in the CKR, we extend the paleolimnologic history of the Nakuru–Elmenteita and Naivasha lakes back to 1 Ma. We compare previously published onshore sediments and outcrops of diatomaceous lake sediments from the Nakuru–Elmenteita basin and six profiles from the Naivasha basin, representing major periods of lake transgression, with new sediment sections and detailed structural mapping. Our record is supplemented by data from sediment cores obtained from the Nakuru–Elmenteita and Naivasha basins (Richardson and Richardson, 1972; Richardson and Dussinger, 1986) and geologic mapping by Blisniuk (1988) and Clarke et al. (1990). Age control is provided by radiocarbon dating of freshwater-snail shells sampled from lake sediments, combined with $^{40}Ar/^{39}Ar$ single-crystal dating of intercalated tuffs (Figs. 3 and 4; Table 2).

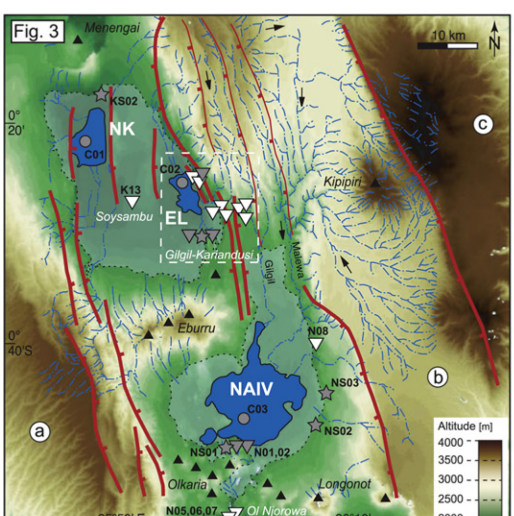
To trace characteristic hydrochemical and hydrologic trends in lake history, we compare fossil diatom assemblages preserved in the lacustrine deposits with modern samples (data from Talling and Talling, 1965; Gaudet and Melack, 1981; Richardson and Dussinger, 1986; Gasse et al., 1995). Periods of lake-level highstands and intermittent lowstands were reconstructed from sediment characteristics and the ecologic signature (i.e., water depth, pH) of the diatom assemblages. Subsequently, diatom assemblages of synchronous lake phases in both basins were compared and linked to rift-related morphological changes in the catchment and climate oscillations.

Based on the compilation of own data and data from the literature, an individual determination of fossil diatom assemblages in each stratigraphic level and paleolimnologic classification of the fossil diatom flora was carried out in two steps. First, characteristic diatom assemblages were defined by averaging corresponding stratigraphic levels of all relevant sedimentary sections. The diatom taxa were determined following the principles of Hustedt (1949), Gasse (1986), and Krammer and Lange-Bertalot (1991a,b, 1997a,b). Since most stratigraphic levels contain similar diatom assemblages characterized by a mixture of planktonic and periphytic taxa, the lake deposits suggest near-shore habitats providing favorable conditions to both, littoral (mostly epiphytic) and planktonic diatoms (cf., Battarbee, 1986, 2000; Smol et al., 2001). In such environments, the relative fraction of eu-planktonic versus facultative planktonic (planktonic species, which primarily live in near-shore habitats, but also exist in the eu-planktonic communities) and epiphytic diatoms is an approximate, qualitative proxy for paleowater depth.

In a second step, the ecologic preference of the most prominent taxa, such as diatom-specific habitat, provided important constraints on the geometry of the water body, i.e., water depth and lake size (Gasse, 1986; Birks et al., 1990; Fritz et al., 1991). An estimate of the hydrochemical conditions was derived from optimum values, such as pH and conductivity of the most frequent diatoms

Table 1
Summarizes physical parameters of modern and reconstructed paleolakes in the Nakuru–Elmenteita and Naivasha basins. Modern data from Milbrink (1977), Gaudet and Melack (1981) and Gasse et al. (1995); paleodata derived from digital-elevation-model based reconstructions (Bergner et al., 2003; Dühnforth et al., 2006). Late-Pleistocene numbers for the Nakuru–Elmenteita basin (italic) are rough estimates. Note detailed outcrop information and stratigraphy given in Table 2 (and Fig. 6 for details of Gilgil–Kariandusi area).

Modern catchments	Nakuru–Elmenteita basin		Naivasha basin
Drainage area [km²]	2390		3240
Modern lakes	Nakuru	Elmenteita	Naivasha
Lake level [m a.s.l.]	1760	1786	1888
Lake area [km²]	40	26	146
Max. lake depth [m]	2	0.5	8
pH	9.7	10.9	7.8
Conductivity [μS cm^{-1}]	25,000	30,000	250
Paleolakes			
Holocene:			
Max. lake level [m a.s.l.]	1940		2000
Max. lake area [km²]	755		685
Max. lake depth [m]	180		140
Late-Pleistocene:			
Max. lake level [m a.s.l.]	*~1900*		1900
Max. lake area [km²]	*~500*		520
Max. lake depth [m]	*100*		150



Tab. 1

modern catchments	Nakuru-Elmenteita basin		Naivasha basin
drainage area [km²]	2,390		3,240
modern lakes	Nakuru	Elmenteita	Naivasha
lake level [m a.s.l.]	1,760	1,786	1,888
lake area [km²]	40	26	146
max. lake depth [m]	2	0.5	8
pH	9.7	10.9	7.8
conductivity [μS·cm^{-1}]	25,000	30,000	250
paleolakes			
Holocene:			
max. lake level [m a.s.l.]	1,940		2,000
max. lake area [km²]	755		685
max. lake depth [m]	180		140
Late Pleistocene:			
max. lake level [m a.s.l.]	*~ 1,900*		1,900
max. lake area [km²]	*~ 500*		520
max. lake depth [m]	*~ 100*		150

Fig. 3. Compilation of modern versus paleolake data in the Central Kenya Rift, showing (A) a topographic map (SRTM-derived topography) with modern Lakes Nakuru (NK), Elmenteita (EL), Naivasha (NAIV), drainage systems (dashed blue with arrows indicating flow direction) and major volcanic centers (black triangles) on the rift floor, bordered by the (a) Mau Escarpment, (b) Kinangop Plateau, (c) Aberdare Ranges. Solid (red) lines mark principal areas of active tectonics during the last one million years. Maximum extend of (Holocene) paleolakes (blue shading) is indicated as inferred from sediments outcrops (triangles), paleo-shorelines (asterisks) and sediment cores (circles). Outcrop patterns refer to datasets of mid- to late-Pleistocene (white) and Holocene (grey) lake periods.

(cf., Hecky and Kilham, 1973; Gasse, 1980; van Dam et al., 1994; Gasse et al., 1995; Gasse et al., 1997). Based on sediment characteristics and reconstructed diatom assemblages, we are able to define separate phases in paleolake evolution, here termed 'initial', 'intermediate', 'highstand', and 'final stage'. Using radiometric age control and sequence correlation we obtained a cross-basin average of sequence-specific lake evolution, which we use in the assessment of geologic and morphologic evolution of the CKR.

4. Results

4.1. Reconstructing characteristic stages of paleolake evolution in the CKR

Based on the synthesis of existing data (cf., Table 2) and our new radiometric age determinations (Fig. 4, Table 2), the deposition of lake sediments in the CKR occurred during three major episodes: a mid-Pleistocene period at about 1 Ma, a late-Pleistocene period between about 150 and 60 ka BP, and a late-Pleistocene to Holocene period between about 15 and 4 ka BP (Fig. 4). Diatomites and diatomaceous silts were deposited only during these intervals, indicating stable lacustrine conditions with protracted freshwater conditions (cf., Harwood, 1999; Owen, 2002; Trauth et al., 2005; Gasse, 2006). Apart from these episodes, less pronounced periods of higher lake-levels could be inferred from lacustrine silts and clays (Richardson and Dussinger, 1986; Trauth et al., 2003; Bergner and Trauth, 2004). Although it cannot be entirely ruled out that evidence for additional lake highstands was obliterated by erosion or deposition of superseding units, the virtually continuous stratigraphic sections at Kariandusi (cf., Fig. 4) strongly suggest that no larger lake transgressions occurred in the intervals between the three principle lacustrine episodes (cf. Trauth et al., 2007). We therefore consider the diatomite-bearing profiles to be unique records and infer that these records correspond to prominent periods of high lake levels during the last 1 Ma.

4.1.1. Mid-Pleistocene lake period (~1 million years BP)

Mid-Pleistocene diatomites are at present only exposed in the southeastern part of the Nakuru–Elmenteita basin, but corresponding basinward facies are most likely down-faulted and covered by younger volcanic and sedimentary units in the Naivasha basin (Figs. 3 and 4; Table 2). At several localities near Gilgil and Kariandusi (Fig. 3), close to the eastern shore of modern Lake Elmenteita, the deposits cover trachytes dated at 1.050 Ma (McCall et al., 1967) and 0.987 ± 0.003 Ma (Trauth et al., 2007), respectively. The diatomites at Gilgil/Kariandusi are up to 31 m thick and unconformably overlain by 0.977 ± 0.010–0.946-m.y.-old pyroclastic deposits (Evernden and Curtis, 1965; Trauth et al., 2007). Since this volcanic unit defines the end of the paleolake highstand, the lacustrine period most likely existed between ~0.99 and ~0.97 Ma.

The mid-Pleistocene diatomite beds are very pure, white, and well stratified. Diatom frustules are well preserved and without evidence of chemical corrosion. Most of the diatom sections contain a deep and freshwater flora, dominated by planktonic *Stephanodiscus transylvanicus*, *Stephanodiscus niagarae* and *Aulacoseira granulata*, without benthic and epiphytic taxa (Fig. 4). Only in the lower and higher parts of the sections, minor amounts of littoral species, such as *Fragilaria construens*, *Fragilaria brevistiata* and *Fragilaria pinnata* appear, and higher amounts of *Cyclotella meneghiniana* and *Rhopalodia* spp. document lower lake levels and possibly higher alkalinity in the initial and final stages of this lake period. Hydrochemical optima, as inferred from the diatom

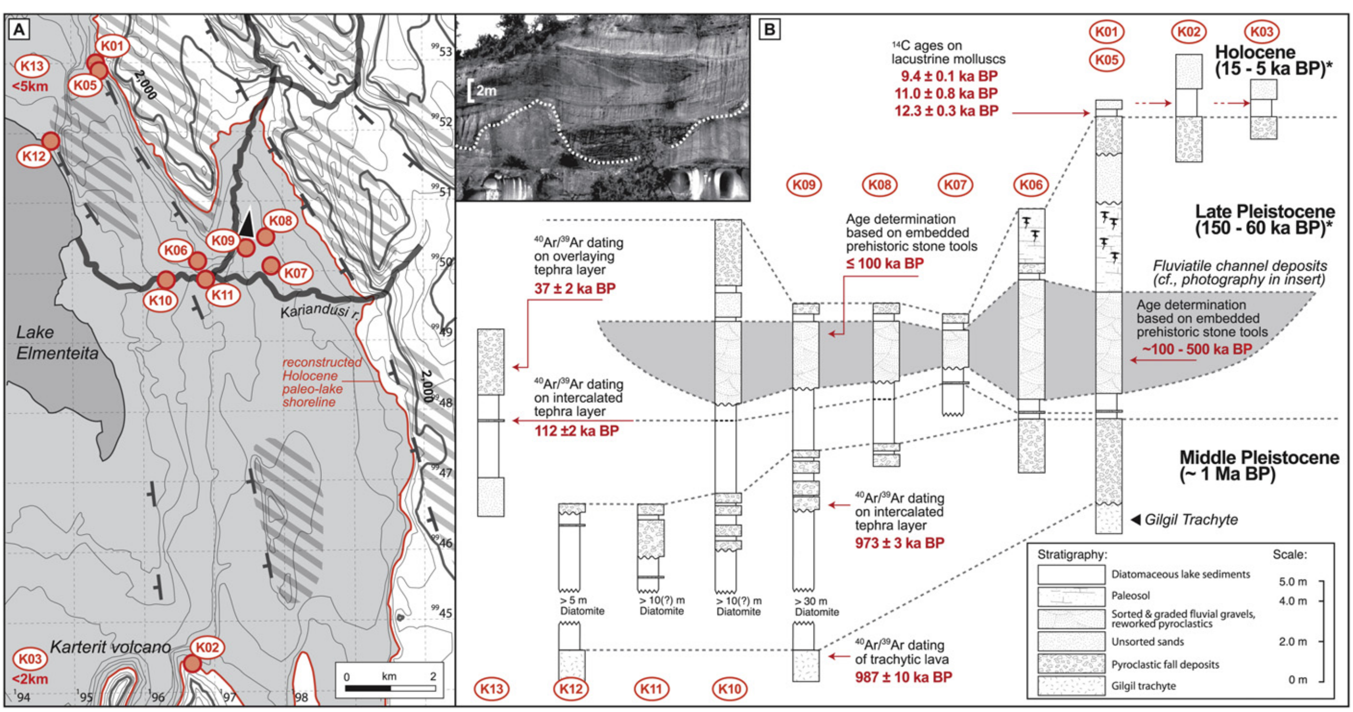


Fig. 4. Map and stratigraphic correlation of surface outcrops in the Gilgil–Kariandusi area used for paleohydrological reconstruction. (A) Sketch of topography (contours in 20 m intervals) showing maximum extend of Holocene paleolake (1940-m-contour; grey shading) and location of sediment sequences E and SE of modern Elmenteita lake as well as main NNW–SSE oriented normal faults (dashed line) with aligned NE-tilted fault-blocks (shadings refer to high topographic relief in the W and gentle E-tipping of hanging walls). (B) Stratigraphic correlation of main periods of lake transgression is based on sedimentology (see text for details) as well as ^{14}C- and ^{40}Ar/^{40}Ar age control. ^{40}Ar/^{39}Ar ages are given with 1 sigma standard deviation. Definition of time intervals of late-Pleistocene and Holocene lake periods incorporates ages of parallel sequences in the northern Nakuru–Elmenteita and Naivasha basins (not shown; cf., Fig. 2, Table 2 and text for details). Photograph in insert shows 100–500-ka-old coarse fluvial sediments, deposited over an erosional unconformity in late-Pleistocene sediments (see text for details).

Table 2
Catalog of sediments sequences in the Nakuru–Elmenteita and Naivasha basins and data from the literature listing topographic elevation, age determinations, dating methods and general sediments characteristics. Notes: (1) Conventional radiocarbon ages on bulk sediment materials (Richardson and Dussinger, 1986) were calibrated using CALIB REV.4.2 (Stuiver and Reimer, 1993). ^{40}Ar/^{39}Ar ages are given with 1 sigma standard deviation.

Nr.	Local name	Elevation [m a.s.l.]	Age [ka BP]	Dating method and reference	Sequence thickness [cm]	Sediment characteristics
Nakuru–Elmenteita basin						
Sediment profiles:						
C01	Nakura core	1750 ± 5	~4.1	ca ^{14}C; top (Richardson and Dussinger, 1986)[1]	500	Diatomaceos gytia, clay
			–15.2	ca ^{14}C; base (Richardson and Dussinger, 1986)[1]		
C02	Elmenteita core	1780 ± 5	–7.4	ca ^{14}C; top (Richardson and Dussinger, 1986)[1]	800	Diatomaceos gytia, clay
			–14.1	ca ^{14}C; base (Richardson and Dussinger, 1986)[1]		
K01	Elmenteita road cut	1910 ± 10	9.4 ± 0.1	ca ^{14}C; top (Dühnforth et al., 2006)	40	Diatomaceos silts
K02	Karterit	1930 ± 10	11.0 ± 0.8	ca ^{14}C; base (Dühnforth et al., 2006)	70	Siltic diatomite
K03	Lemulug	1930 ± 10	12.3 ± 0.3	ca ^{14}C; top (Dühnforth et al., 2006)	90	Siltic diatomite
K13	Soysambu	1880 ± 10	114 ± 2	^{40}Ar/^{39}Ar; intercalated tephra (Bergner et al., in review)	450	Soft diatomite
K05	Elmenteita road cut	1900 ± 10	<973	Stratigraphic correlation and pers. comm. to A. Deino; new ^{40}Ar/^{39}Ar age in prep.	140	Soft diatomite
K06	Kariandusi road cut	1860 ± 10	<973	Stratigraphic correlation (this work)	100	Soft diatomite
K07	Prehistoric site	1870 ± 10	<973	Stratigraphic correlation (this work)	300	Pure white diatomite
K08	Prehistoric top	1880 ± 10	<973	Stratigraphic correlation (this work)	>160	Pure white diatomite
K10 *b*	Kariandusi gorge	1830 ± 10	<973	Stratigraphic correlation (this work)	500	Pure white diatomite
K09	Kariandusi mine	1840 ± 10	~946	K/Ar; top (Evernden & Curtis, 1965; pub. without error bars; Trauth et al., 2007)	3100	Pure white diatomite
			973 ± 3	^{40}Ar/^{39}Ar; top (Trauth et al., 2005; Trauth et al., 2007)		
			987 ± 10	^{40}Ar/^{39}Ar; base (Trauth et al., 2005; Trauth et al., 2007)		
			~1050	K/Ar; base (Strecker et al., 1990; Trauth et al., 2007)		
K10 *a*	Kariandusi gorge	1830 ± 10	>973	Stratigraphic correlation (this work)	>1000	Pure white diatomite
K11	Kariandusi river gully	1860 ± 10	>973	Stratigraphic correlation (this work):	>1000	Pure white diatomite
K12	Elmenteita beach	1790 ± 10	>973	Stratigraphic correlation (this work)	>500	Pure white diatomite
Paleo-shorelines:						
KS01	Karterit	1935 ± 10	15–4	Stratigraphic correlation (Dühnforth et al., 2006)		
KS02	Menengai	1940 ± 10	12–6	Stratigraphic correlation (Washbourn-Kamau, 1970)		
Naivasha basin						
Sediment profiles:						
C03	Naivasha core	1880 ± 5	~4.7	^{14}C; top (Richardson and Dussinger, 1986)[1]	500	Diatomaceos, gytia, clay
			~14.7	^{14}C; base (Richardson and Dussinger, 1986)[1]		
N01	Oserian Farm	1950 ± 10	12–6	Stratigraphic correlation (this work)	70	Siltic diatomite
N02	Mundui Estate	1960 ± 10	12–6	Stratigraphic correlation (this work)	80	Siltic diatomite
N07	Central Tower	1860 ± 10	81 ± 4	^{40}Ar/^{39}Ar; top (Trauth et al., 2003)	60	Soft diatomite
			73 ± 3	^{40}Ar/^{39}Ar; base (Trauth et al., 2003)		
N06	O1 Njorowa Gorge II	1840 ± 10	108 ± 7	^{40}Ar/^{39}Ar; top (Trauth et al., 2003)	120	Pure white diatomite
			113 ± 2	^{40}Ar/^{39}Ar; base (Trauth et al., 2003)		
N08	Malewa river	1930 ± 20	~140–110	Stratigraphic correlation (this work)	200	Soft diatomite
N05	Ol Njorowa Gorge I	1830 ± 10	141 ± 3	^{40}Ar/^{39}Ar; intercalated tephra (Trauth et al., 2003)	350	Soft diatomite
			146 ± 2	^{40}Ar/^{39}Ar; base (Trauth et al., 2003)		
Paleo-shorelines. beach gravels:						
NS01	Oserian Farm	2000 ± 20	12–6	Stratigraphic correlation (Washbourn-Kamau, 1975)		
NS02	Munyu railway	2005 ± 10	12–6	Stratigraphic correlation (Washbourn-Kamau, 1975)		
NS03	Malewa river	1980 ± 20	12–6	Stratigraphic correlation (Washbourn-Kamau, 1975)		

assemblages that occurred during the highest lake level, indicate neutral to slightly alkaline conditions with a prevailing pH of ~7–7.5 and conductivity values well below 500 μS cm^{-1} (transfer functions based on Gasse et al. (1995)).

The diatom flora dominated by large *Stephanodiscus* spp. and *Aulacoseira* spp. is typical for large freshwater lakes, as has been shown in reconstructions from other lake sediment sequences of similar age in the Kenyan and Ethiopian rifts (e.g., Gasse, 1977; Behrensmeyer et al., 2002; Owen, 2002; Deino et al., 2006; Gasse, 2006). The most likely paleoecological interpretation for the mid-Pleistocene diatomites in the CKR is a depositional environment constituted by a single, areally extensive lake, up to more than 100 m deep. The interpretation of a single large lake is confirmed by the regional geological setting (see below) and similar extensive lake transgressions in the Olorgesailie basin in the Southern Kenya Rift (Behrensmeyer et al., 2002), as well as in the Baringo basin and the Suguta Valley in the Northern Kenya Rift (Trauth et al., 2005).

4.1.2. *Late-Pleistocene lake period (150 to 60 ka BP)*

Lake deposits at Soysambu, west of Lake Elmenteita, and three diatomite sequences in the Ol Njorowa Gorge, south of Lake Naivasha (Figs. 3 and 4; Table 2) document multiple lake-level highstands in the Nakuru–Elmenteita and Naivasha basins during the late-Pleistocene (cf., Bergner and Trauth, 2004; unpublished data for Soysambu as electronic supplement). The oldest of these highstands is documented by a ∼4-m-thick diatomite unit in both basins, intercalated with ∼141 and ∼112-ka-old tuffs and containing virtually identical diatom assemblages. In the Naivasha basin, two additional diatomite beds, ∼110, and ∼80 ka old, document younger lake transgressions that were not observed in the Nakuru–Elmenteita basin (Trauth et al., 2003; Bergner and Trauth, 2004). However, diatomite beds near Gilgil and Kariandusi correspond stratigraphically, which make them equivalent to the late-Pleistocene deposits of Soysambu and Ol Njorowa Gorge. Compared to the diatomite units pertaining to the preceding large-lake phase, these younger diatomite beds contain more abundant phytoliths and clastic particles, and are characterized by reduced preservation of diatom frustules (cf., Bergner and Trauth, 2004; unpublished data for Soysambu as electronic supplement).

The flora of the late-Pleistocene lakes is dominated by abundant facultative planktonic and epiphytic diatoms. Compared to the mid-Pleistocene lake period, the ratio between littoral versus planktonic species is higher, i.e., facultative planktonic and epiphytic diatoms are more abundant (Fig. 5). In particular, *Fragilaria* spp., *Synedra* spp., *Cocconeis placentula*, *Gomphonema* spp. and *Epithemia* spp. dominate throughout the deposits of all late-Pleistocene lake stages. During intervals of the highest lake levels of late-Pleistocene time, the diatom assemblage is dominated by planktonic, but littoral-habitat preferring species *Cyclotella* spp., i.e., *Cyclotella ocellata*, *Cyclotella stelligera* and *C. meneghiniana*. In contrast to the mid-Pleistocene assemblages, the importance of *Aulacoseira ambigua* and *Aulacoseira granulata var. angustissima* increases. Importantly, also halophile diatoms, such as *Thalassiosira faurii* and *Mastogloia elliptica* occur occasionally, reflecting a trend toward more alkaline conditions (cf., Bergner and Trauth, 2004).

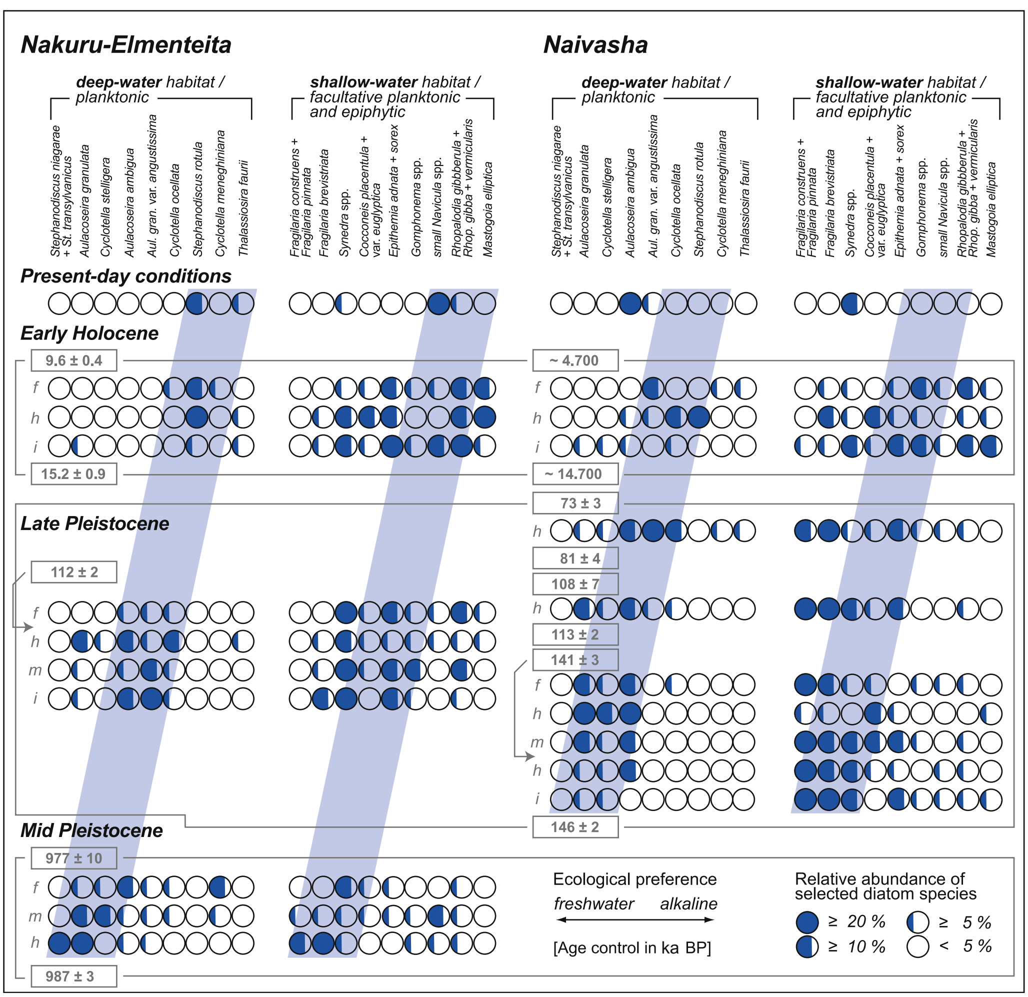


Fig. 5. Results of diatom analyses from Nakuru–Elmenteita and Naivasha basins, showing trend of increasing pH and salinity during lake evolution of the last 1 Myr. Timing of main lake-highstand periods is indicated by maxima and minima of ^{14}C- and $^{40}Ar/^{39}Ar$ ages. $^{40}Ar/^{39}Ar$ ages are given with 1 sigma standard deviation. Relative abundance of selected diatom species corresponds to averaged values from corresponding samples in selected stratigraphic levels (i: initial, m: intermediate, h: highstand, f: final stage of lake succession); circles reflect <5%, ≥5%, ≥10% and ≥20% of relative diatom abundance. Diatom taxa are sorted with respect to their habitat (deep-water versus shallow water) preference and preferred conductivity values (data from Gasse, 1980; van Dam et al., 1994; Gasse et al., 1995).

Although general sediment characteristics as well as diatom assemblages are very similar in the late-Pleistocene deposits of the Nakuru–Elmenteita and Naivasha basins, these sediments were not deposited in the same lake. Oxygen-isotope analysis of diatom frustules from the Soysambu and Ol Njorowa Gorge sections conducted in a new project (unpublished materials in the electronic supplements) reveal that two separate paleolakes existed in the Nakuru–Elmenteita and Naivasha basins between 150 and 110 ka BP, because higher $\delta\,^{18}O$ values in the Nakuru basin at Soysambu compared to Ol Njorowa Gorge data in the Naivasha basin show that paleolake Nakuru experienced stronger evaporation than paleolake Naivasha.

However, stratigraphically well constrained, three-dimensional reconstructions of the Naivasha paleolake bathymetry indicate that up to 150-m-deep lake, which must have been approximately three- to four-times larger than its modern equivalent, existed in the Naivasha basin during highest late-Pleistocene lake levels (Bergner et al., 2003). Taking into account the similarity of sediment characteristics and diatom assemblages in late-Pleistocene deposits of the Nakuru–Elmenteita and Naivasha basins, it is possible that both basins experienced similar lake transgressions, which were characterized by deep (several tens of meters depth) and mostly freshwater (pH $\sim$8; conductivity $\leq$1000 μS cm^{-1}) conditions (transfer functions based on Gasse et al., 1995).

4.1.3. Holocene lake period (15 to 4 ka BP)

Holocene lake sediments in the Nakuru–Elmenteita and Naivasha basins exposed in the vicinity of the modern lakes and in the Gilgil–Kariandusi area are generally thin, i.e., less than 80 cm (Fig. 4; Table 2). These deposits contain significant amounts of clastic particles, phytoliths, and sponge spicules. Diatom preservation is often limited. The compilation of paleoenvironmental data extracted from these sediments and sediment-core data (Richardson and Richardson, 1972; Richardson and Dussinger, 1986) suggests that the Holocene lake-highstand was characterized by comparable hydrologic conditions in both lake basins. The reconstruction of the ancient water bodies as inferred from the elevation of paleo-shorelines suggests that the paleolakes were three- to four-times larger than the present lakes, with volumes 50 to 60 times greater than today (Washbourn-Kamau, 1970, 1975; Bergner et al., 2003; Dühnforth et al., 2006). Similar conditions, although temporally offset, existed in the Suguta Valley in the Northern Kenya Rift, where $\sim$300 m high lake levels were recorded for a Holocene highstand between 16.5 and 8.5 ka BP (Garcin et al., 2009). In the Nakuru–Elmenteita basin, maximum water depth was on the order of 175 $\pm$ 25 m and 130 $\pm$ 10 m in the Naivasha basins, respectively (Bergner et al., 2003; Dühnforth et al., 2006).

Compared to the diatom communities in the mid- and late-Pleistocene sediments, the early-Holocene flora contains more littoral diatoms, even during stages corresponding to highest lake levels. Numerous *Epithemia* spp., *Gomphonema* spp., *Rhopalodia* spp. and *Navicula* spp. are common and typically accompanied by rare planktonic *Stephanodiscus rotula*, *Aulacoseira agassizii* and facultative planktonic *Synedra* spp. Frequent halophile *T. faurii*, *Rhopalodia gibberula* and *M. elliptica*, but absent *F. construens*, and less abundant *C. ocellata* reflect increasing alkalinity in both lake basins (Fig. 5). The reconstructed hydrochemical parameters show a much higher variability between the initial, highstand, and final stages of the lake periods, respectively. Conductivity estimates obtained from dominant diatom taxa decrease from 2000 to 750 μS cm^{-1} during the transition from initial to highstand stages. The estimated pH was generally higher than 9.0, but was reduced to less than 8.0 during the inferred highest lake levels (transfer functions based on Gasse et al. (1995)).

4.2. Distinguishing tectonic versus climatic controls on paleolake evolution

4.2.1. Long-term hydrologic and paleoenvironmental evolution

The paleohydrologic conditions inferred from sediment characteristics and diatom assemblages suggest a rather similar hydrologic evolution in the two CKR lake basins during the last million years. 1 Ma-old sediments yield the first evidence for a major lake transgression covering the rift floor with probably a single large lake, which was sustained for at least several thousand years. Such a lake must have been comparable to some rift lakes of the western branch of the EARS today. The paleolake reconstruction fits well into the general tectonic framework prior to the change in extension direction when the CKR was less internally segmented by normal faults and intervening volcanic edifices (Baker et al., 1988; Clarke et al., 1990; Strecker et al., 1990; Bosworth and Strecker, 1997). Thus, since the inner rift was not yet compartmentalized into smaller subbasins, this environment provided extensive accommodation space to host a single, large mid-Pleistocene lake (Fig. 8). Increased humid conditions that coincide with a 400 ka eccentricity maximum at 1.1–0.9 Ma suggest that insolation-driven climate variations may provide the most plausible explanation for the major lake transgression (cf., Trauth et al., 2009). The appearance of *Stephanodiscus* spp. not only in the sediments of the CKR (Trauth et al., 2007), but also in Ethiopian lake deposits of similar age (Gasse, 1980) further support the notion of a major wet interval at $\sim$1 Ma (Trauth et al., 2005; Gasse, 2006).

However, comparing the mid-Pleistocene lake highstand to subsequent lake transgressions during the late-Pleistocene and early Holocene clearly shows that subsequent highstands were less pronounced. This trend has been accompanied by a long-term shift towards a mid-Pleistocene to Holocene predominance of epiphytic, more brackish-water diatom species (Fig. 5). In addition, the absolute thickness of the diatomaceous lake sediment sequences and their degree of purity decrease continuously from mid-Pleistocene to Holocene units, reflecting a decrease in duration and importance of lacustrine episodes. The trend toward increased detritus in the youngest deposits is furthermore accompanied by a reduced preservation of diatom frustules. Since detrital content and degree of diatom preservation correlate with proximity of the sampling site to shoreline environments and ionic enrichment of the former water body, these observations also confirm the interpretation of continuously decreasing water depths through time (cf., Hecky and Kilham, 1973; Gawthorpe and Leeder, 2000; Owen, 2002; Gasse, 2006).

4.2.2. Tectonic forcing of drainage conditions

Although a tendency towards shallower, more saline lakes is observed in many East African rift basins (e.g., Hecky and Kilham, 1973; Stoffers and Hecky, 1978; Eugster and Jones, 1979; Gasse, 1990; Owen, 2002), the evolution of the CKR during the mid-Pleistocene time emphasizes the prominent role of volcano-tectonic controls on the differentiation of the initially larger rift basins (Strecker et al., 1990; Clarke et al., 1990). Since the mid-Pleistocene, volcano-tectonic activity in the CKR has been focused on the inner rift, producing a closely spaced pattern of small-scale faults and volcanic centers, along and between individual segments of the rift axis. The closure of the Naivasha basin by the onset of activity of Mt. Eburru at $\sim$400 ka BP and the Olkaria Volcanic Complex in the south at about 320 ka BP, as well as the northern closure of the Nakuru–Elmenteita basin by the Mt. Menengai Caldera at $\sim$180 ka BP initiated the separation and hydrologic isolation of the Nakuru–Elmenteita and Naivasha lake basins

(Clarke et al., 1990; Scott and Skilling, 1999; Trauth et al., 2003; Bergner et al., 2003). Subsequent sediment infilling coupled with continued slow tectonic basin subsidence may have led to the observed change in lacustrine dynamics.

However, the general, volcanically and tectonically controlled trend toward basin isolation and disparate sedimentary environments were further exacerbated by the diversion of runoff from catchment areas with higher precipitation. In particular, the propagation of normal faults in the Gilgil–Kariandusi area created a complex geometry of tilted, small-scale horst structures straddling the Kinangop Plateau (cf., Baker et al., 1988; Roessner and Strecker, 1997) (Fig. 6). Particularly, the two main normal faults that bound the Naivasha and Elmenteita basins lose throw at their northern and southern tips, respectively (cf., Figs. 6 and 7). Warping of the footwall block and formation of additional small-scale normal faults between the tips of both (main) faults have created a topographically low-lying area that provides an ideal entry point for runoff sourced from the Kinangop Plateau and the Aberdare Ranges on the eastern rift margin (Fig. 7). An additional cause for the final separation of the Nakuru–Elmenteita and Naivasha basins was the formation of left-stepping en échelon horst and graben structures, which kinematically link the individual extension zones along the volcano-tectonic axis of the CKR (Strecker et al., 1990; Bosworth and Strecker, 1997).

Importantly, routing of drainage around propagating fault tips along the Kinangop Plateau must have ultimately blocked westward directed runoff, causing southward drainage diversion towards the Naivasha basin, while leaving much smaller contributing areas for the Elmenteita–Nakuru basins. In contrast to the initial rift stage of the CKR, where river discharge supplied one large basin, tectonically controlled drainage diversion thus resulted in preferred discharge to the Naivasha basin coupled with a significant decline of the precipitation–evaporation (P–E) ratio in the Nakuru–Elmenteita basin. Moreover, the tectonically controlled segmentation of the drainage systems subsequently led to the separation of two individual catchments, with the area of the Naivasha catchment (3240 km^2) almost 1.5 times larger than the Nakuru–Elmenteita catchment (2390 km^2).

Our interpretation of dramatically reduced discharge to the Nakuru–Elmenteita basin in the course of tectonically controlled late- to mid-Pleistocene deflection of upstream river systems is supported by coarse fluvial conglomerates deposited over an erosional unconformity cutting mid-Pleistocene diatomites at Gilgil and Kariandusi (Fig. 4 and insert). Reworked Acheulian handaxes in these deposits define a minimum age of 0.7–1.0 Ma BP (cf., Gowlett and Crompton, 1994), but lateral pinch-outs of horizons bearing much more advanced (Middle Stone Age) tools suggest an even younger, late-Pleistocene age (~100–

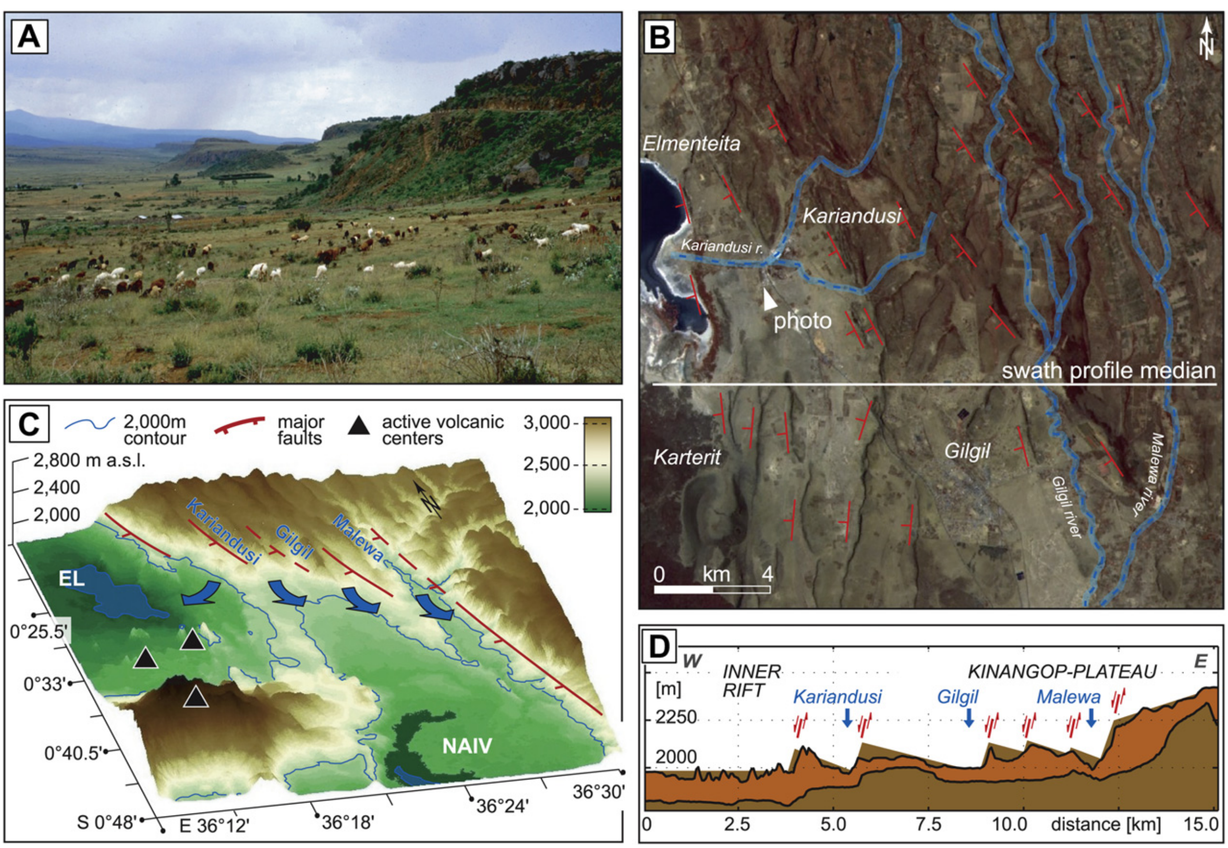


Fig. 6. Regional settings of the area between Gilgil and Kariandusi, where propagating normal faults deflected runoff from high catchment areas. (A) Photography of Gilgil/Kariandusi landscape showing W dipping fault-blocks along the Kinangop Plateau. (B) ASTER-satellite image of Gilgil/Kariandusi area showing location of Lake Elmenteita, main river channels (dotted blue lines) as well as fault-block signatures (dark contours). The location of landscape picture (in A) and swath profile (in D) is indicated. (C) SRTM-derived present-day morphology of extended area spanning Eburru, Karterit and Lemulug volcanic centers (black triangles) and valleys of Kariandusi, Gilgil and Malewa rivers. High-resolution topography illustrates narrow arrangement of tilted fault-blocks and deflection of river drainage (arrows) along Kinangop Plateau (to the east). Present-day lakes Elmenteita (EL) and Naivasha (NAIV) as well as 2000-m contour (blue line) are indicated. (D) Topographic swath profile (orange; borders defined by min and max values) overlying schematic cross section (brown shading) through the Gilgil–Kariandusi area illustrating the domino-style arrangement of W dipping normal faults and fault-blocks as well as footwall restricted flow of main rivers (cf., Fig. 7). W–E swath profile is 6 km wide and centered along the S 0°30′ latitude, mostly perpendicular to the direction of main tectonic faults and river channels. Topography data (orange filling with solid lines denoting max–min ranges) derived from SRTM dataset (USGS).

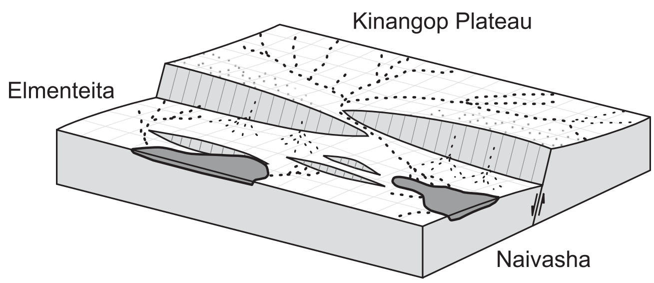


Fig. 7. En échelon fault tips of main faults bounding the eastern margin of the Naivasha and Elmenteita basins and fluvial network evolution. Discharge generating from the Kinangop Plateau and Aderdare Ranges is routed through an entry point between fault tips into the Naivasha basin (after Yielding and Roberts, 1992).

70 ka BP; Blisniuk, 1988) for this cut-and-fill event. The provenance of the fluvial deposits indicates a larger catchment area in the east and documents higher transport capacity from the Kinangop Plateau and Aberdare Ranges into the Nakuru–Elmenteita basin before drainage-system reorganization occurred (Figs. 6 and 7).

5. Discussion and conclusions

The hydrologic changes in the Nakuru–Elmenteita and Naivasha basins document the complex interaction between climatic and tectonic influences on lake-basin evolution. The synchroneity of prominent lake transgression at 1 Ma, between 150–60 ka and 15–5 ka BP in the CKR and other East African lake basins, such as in the northern Kenya Rift (e.g., Butzer et al., 1969; Sturchio et al., 1993; Deino et al., 2006; Garcin et al., 2009), the southern Kenya Rift (e.g., Hillaire-Marcel et al., 1986; Casanova and Hillaire-Marcel, 1992; Behrensmeyer et al., 2002) and other places in East Africa (e.g., Gasse, 2000) suggests that prominent insolation-driven episodes of a wetter climate were responsible for high lake levels in the region (e.g., Trauth et al., 2005). However, there is evidence for coeval lake regression in a new dataset from the Malawi rift (Scholz et al., 2007). Interestingly, such temporal disparities exist at all timescales in the EARS, e.g., during the late-Pleistocene (e.g., Partridge et al., 1997; Trauth et al., 2003) or during the early Holocene, when lake-level records from the Northern Kenya Rift are out of phase with data from the Central Kenya Rift and the Ethiopian Rift (e.g., Garcin et al., 2009). This apparent contradiction could result from a different response of rift-basin lakes to orbitally

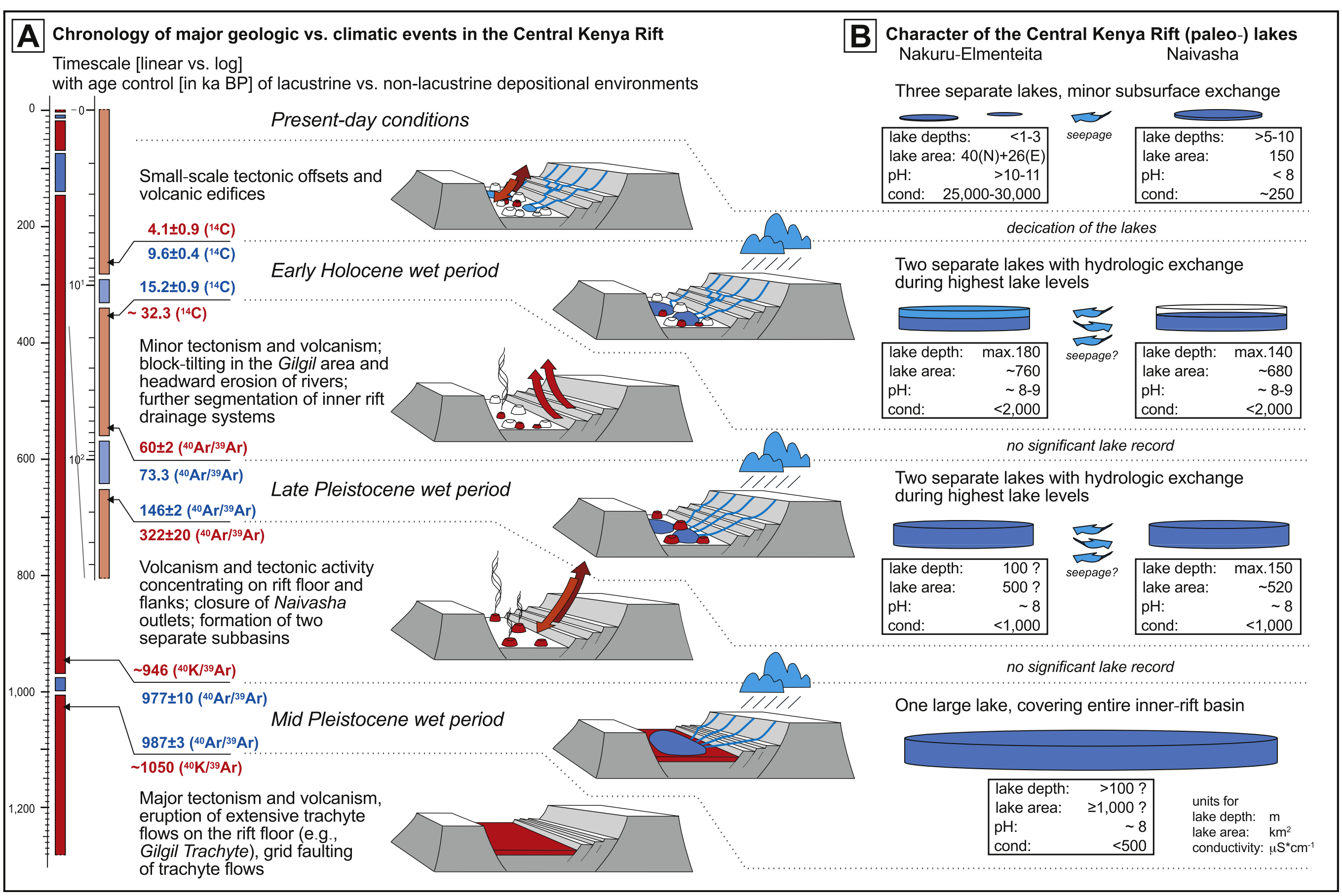


Fig. 8. Scheme of tectono-morphologic versus hydro-climatic influences on the hydrologic evolution of Central Kenya Rift (CKR) and status of lakes Nakuru, Elmenteita and Naivasha during prominent time-slices during the last 1 Ma. Area shown corresponds to map extensions in Fig. 1. (A) Chronology of major geologic and climatic events shows evolution of the CKR from initiation stage with trachytic volcanism (red) and major NW-orientated normal faulting along Mau Escarpment, Kinangop Plateau and Aberdare Ranges towards minor normal faulting (arrows) propagating along the Kinangop Plateau and Late-Pleistocene separation of Naivasha and Nakuru–Elmenteita basins. Whereas high river runoff (blue) from rift-shoulders allows formation of a large and deep freshwater lake during the Mid-Pleistocene, river deflection and drainage reversal on up-thrown footwalls led to preferential drainage into southern Naivasha basin. (B) The status of rift lakes at present-day (data from literature, see text for details) and during major climatic wet events as reconstructed from diatom assemblages, sediment characteristics and lake-balance modeling reflects the synchronous formation of large freshwater lakes in the Nakuru-Elmenteita and Naivasha basins, but decreasing water volumes and higher conductivity values through time. Net hydrologic coupling of lake basins and subsurface-water exchange is suggested to have balanced hydrologic deficiencies, which are more obvious during climatic dry intervals (such as today). $^{40}Ar/^{39}Ar$ ages are given with 1 sigma standard deviation.

driven insolation variations and different latitudinal positions of these basins within the N–S oriented EARS.

In any case, the reconstructed paleohydrolgic variations in the CKR were superimposed on a long-term trend towards smaller water bodies and increasing alkalinity, as suggested by the succession of diagnostic diatom assemblages as well as changing sediment characteristics in the Naivasha and Nakuru–Elmenteita basins (Fig. 8). This long-term trend has been observed in many East African lake basins (e.g., Hecky and Kilham, 1973; Stoffers and Hecky, 1978; Eugster and Jones, 1979; Gasse et al., 1997; Owen, 2002). The phenomenon is commonly explained as a consequence of reduced basin subsidence, accompanied by higher sediment supply with subsequent filling of the basin (Yuretich, 1982; Baker et al., 1972; Tiercelin and Lezzar, 2002). Although the increased sediment input is difficult to prove in the tectonically and magmatically dominated CKR, such a process may have potentially operated here as well (cf., McCall et al., 1967; Strecker et al., 1990). In such a scenario, the shift in the mid-Pleistocene to Holocene diatom flora from deep-water indicators toward shallow-lake communities could therefore primarily reflect the long-term sedimentary evolution toward more complex and smaller basin geometries in the CKR, which might have been additionally influenced by strengthened East African aridity and more severe hydrologic conditions in the course of global climate transitions (e.g., DeMenocal, 2004; Trauth et al., 2009).

However, the structurally controlled segmentation of the CKR and the differentiation of catchment areas have complicated the overall lake-basin evolution and may be equally important, and perhaps exerted more dominant influence, at least during drier periods. Interestingly, lake sediments of late-Pleistocene and Holocene lake-level highstands do not entirely reflect the differentiation of catchment areas after ~0.9 Ma BP. Although some parameters indicate a slightly higher evaporative stress and slightly more ionic enrichment in the Nakuru–Elmenteita sediments, principal diatom assemblages of the 150–60 and 15–4 ka BP lake periods indicate similar paleohydrologic and hydrochemical conditions in both basins (Fig. 5). In order to understand the contrasting paleoenvironmental data and to better assess the distinct impact of tectonic versus climatic influences on the hydrologic conditions in the CKR, we additionally compare our results with previously applied lake-balance modeling approaches to the reconstructed Holocene paleo-lake highstands in the Naivasha (Bergner et al., 2003) and Nakuru–Elmenteita basins (Dühnforth et al., 2006).

The lake-balance modeling used in our previous studies suggest a long-term increase in precipitation of about 30–45% as the main cause for Holocene lake-level highstands (Bergner et al., 2003; Dühnforth et al., 2006). Accordingly, Holocene precipitation rates for the Nakuru–Elmenteita basin should have been about 20–25% higher than those of the Naivasha basin. Taking into account the close proximity of the lake basins and the similarity of the overall physiogeographic setting, such an inferred rainfall gradient is highly unrealistic. Instead, we suggest hydrologic linkage between the CKR basins associated with a significant subsurface-water exchange from the Naivasha toward the Nakuru–Elmenteita basin. Since sediment characteristics and diatom reconstructions reflect a more similar lake behavior and paleoecological conditions during the periods of paleo-lake highstands, we suggest subsurface–hydrologic coupling to have balanced the negative moisture budget of the Nakuru–Elmenteita basin during protracted humid periods. Conversely, during drier conditions, the water supply is insufficient to compensate for this deficit. Since groundwater exchange between the modern Naivasha and Nakuru–Elmenteita basins is well documented (cf., Becht and Harper, 2002), intensified hydrologic coupling in the past may explain similar paleohydrologic responses in both basins at short-term intervals of extreme humid conditions.

In conclusion, although sediments in the EARS represent excellent natural archives of past climate change, the interpretation of lake records from tectonically active extensional regions requires a careful assessment of tectonic and volcanic forcing on sedimentation and lake history, even on short timescales of 10^4–10^3 years. To date, there are only a few examples, which have demonstrated the far-reaching influence of tectonic control on the differentiation of catchment areas in East African rift basins Because of the ongoing tectonic processes in EARS, changes of lake level and hydrochemistry must be interpreted with care and do not automatically reflect the effects of climatic change. Instead, these characteristics may result from conspiring complex tectono-magmatic and geomorphic processes. This may influence rainfall amount and distribution, as well as catchment size and runoff, and thus the hydrochemistry of the lake basins. Although our study highlights the particular extent of hydrologic changes in the tropics during climatically extreme periods, the recent hydrologic setting of the lakes in the EARS and their long-term history underscores the need for integrated geomorphic, structural, and paleoecological studies in attempts to decipher and deconvolve the climatic history contained in the lacustrine sediments of East Africa.

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Appendix. Supplementary data

Supplementary information related to this article can be found in online version at doi: 10.1016/j.quascirev.2009.07.008.

References

Åse, L.E., 1987. A note on the water budget of Lake Naivasha, Kenya – especially the role of *Salvinia molesta* Mitch and *Cyperus papyrus* L. Geographiska Annaler 69A (3–4), 415–429.

Baker, B.H., Mohr, P.A., Williams, L.A.J., 1972. Geology of the eastern rift system of Africa. Geological Society American Special Papers 136.

Baker, B.H., Mitchell, J.G., Williams, A.J., 1988. Stratigraphy, geochronology and volcano-tectonic evolution of the Kedong–Naivasha–Kinangop region, Gregory Rift Valley, Kenya. Journal of the Geological Society, London 145, 107–116.

Baker, B.H., Wohlenberg, J., 1971. Structure and evolution of the Kenya Rift Valley. Nature 229, 538–542.

Battarbee, R.W., 1986. Diatom analysis. In: Berglund, B.E. (Ed.), Handbook of Holocene Palaeoecology and Palaeohydrology. John Wiley & Sons, Chichester.

Battarbee, R.W., 2000. Paleolimnological approaches to climate change, with special regard to the biological record. Quaternary Science Reviews 19, 107–124.

Becht, R., Harper, D., 2002. Towards an understanding of human impact upon the hydrology of Lake Naivasha. Hydrobiologia 488, 1–11.

Behrensmeyer, A.K., Potss, R., Deino, A., Ditchfield, P., 2002. Olorgesaille, Kenya: a million years in the life of a rift basin. In: Renaut, R.W., Ashley, G.M. (Eds.), Sedimentation in Continental Rifts. SEPM Special Publications, vol. 73, pp. 97–106.

Bergner, A.G.N., Trauth, M.H., Bookhagen, B., 2003. Paleoprecipitation estimates for the Lake Naivasha basin (Kenya) during the last 175 k.y. using a lake-balance model. Global and Planetary Change 36, 117–136.

Bergner, A.G.N., Trauth, M.H., 2004. Comparison of the hydrologic and hydrochemical evolution of Lake Naivasha (Kenya) during three highstands between 175 and 60 kyr BP. Palaeogeography, Palaeoclimatology, Palaeoecology 215, 17–36.

Birks, H.J., Line, J.M., Juggins, S., Stevenson, A.C., TerBraak, C.J.F., 1990. Diatoms and pH reconstruction. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences 327, 236–278.

Blisniuk, P.M., 1988. Geologie des Lake Elmenteita Gebiets, Zentrales Kenya Rift. Unpublished diploma thesis, University of Karlsruhe.

Bosworth, W., Strecker, M., 1997. Stress field changes in the Afro-Arabian rift system during the Miocene to recent period. Tectonophysics 278, 47–62.

Butzer, K.W., Brown, F.W., Thruber, D.L., 1969. Horizontal sediments of the lower Omo Valley; the Kibish formation. Quaternaria 11, 15–29.

Casanova, J., Hillaire-Marcel, C., 1992. Chronology and paleohydrology of Late Quaternary high lake levels in the Manyara basin (Tanzania) from isotopic data (18O, 13C, 14C, Th/U) on fossil stromatolites. Quaternary Research 38, 205–226.

Clarke, M.C.G., Woodhall, D.G., Allen, D., Darling, G., 1990. Geological, Volcanological and Hydrogeological Controls on the Occurrence of Geothermal Activity in the Area Surrounding Lake Naivasha, Kenya. British Geological Survey Report and Govt. of Kenya – Ministry of Energy, Nairobi, Kenya.

Deino, A.L., Kingston, J.D., Glen, J.M., Edgar, R.K., Hill, A., 2006. Precessional forcing of lacustrine sedimentation in late Cenozoic Chemeron Basin, Central Kenya Rift, and calibration of the Gauss/Matuyama boundary. Earth and Planetary Science Letters 247, 41–60.

Delvaux, D., Kervyn, F., Vittori, E., Kajara, R.S.A., Kilembe, E., 1998. Late Quaternary tectonic activity and lake level change in the Rukwa Rift Basin. Journal of African Earth Sciences 26 (3), 397–421.

DeMenocal, 2004. African climate change and faunal evolution during the Pliocene–Pleistocene. Earth and Planetary Science Letters 220, 3–24.

Dühnforth, M., Bergner, A.G.N., Trauth, M.H., 2006. Early Holocene water budget of the Nakuru–Elmenteita basin, Central Kenya Rift. Journal of Paleolimnology 36, 281–294.

van Dam, H., Mertens, A., Sinkeldam, J., 1994. A coded checklist and ecological indicator values of freshwater diatoms from The Netherlands. Netherlands Journal of Aquatic Ecology 28 (1), 117–133.

Ebinger, C.J., Rex, D.C., Yemane, T., Kelley, S., 1993. Volcanism and extension between the Ethiopian and Gregory rifts. In: Thorweihe, U., Schädelmeier, H. (Eds.), Geoscientific Research in Northeastern Africa. Balkema, Rotterdam, pp. 301–304.

Ebinger, C.J., Yemane, T., Harding, D.J., Tesfaye, S., Kelley, S., Rex, D.C., 2000. Rift deflection, migration, and propagation: linkage of the Ethiopian and Easter rift, Africa. GSA Bulletin 112 (2), 163–176.

Eugster, H.P., Jones, B.F., 1979. Behavior of major solutes during closed-basin brine evolution. American Journal of Science 279, 609–631.

Evernden, J.G., Curtis, G.H., 1965. The potassium–argon dating of late Cenozoic rocks in East Africa and Italy. Current Anthropology 6, 177–189.

Foster, D.A., Gleadow, A.J.W., 1996. Structural framework and denudation history of the flanks of the Kenya and Anza Rifts, East Africa. Tectonics 15 (2), 258–271.

Fritz, S.C., Juggins, S., Battarbee, R.W., Engstrom, D.R., 1991. Reconstruction of past changes in salinity and climate using a diatom-based transfer function. Nature 352, 706–708.

Garcin, Y., Junginger, A., Melnick, D., Olago, D.O., Strecker, M.R., Trauth, M.H., 2009. Late Pleistocene–Holocene rise and collapse of the Lake Suguta, northern Kenya Rift. Quaternary Science Reviews 28 (9–10), 911–925.

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

Gasse, F., 1980. Les Diatomées Lacustres Plio-Pléistocenes du Gadeb (Éthiopie). Revue Algologique, Mémoire Hors-série, vol. 3, Paris.

Gasse, F., 1986. East African Diatoms – Taxonomy, Ecological Distribution. Cramer, Stuttgart. Bibliotheca diatomologica 11.

Gasse, F., 1990. Tectonic and climatic controls on lake distribution and environments in Afar from Miocene to present. In: Katz, B.J. (Ed.), Lacustrine Basin Exploration, Case Studies, and Modern Analogs. AAPG Memoir, vol. 50, pp. 19–41.

Gasse, F., 2000. Hydrological changes in the African tropics since the Last Glacial maximum. Quaternary Science Reviews 19, 189–211.

Gasse, F., 2006. Climate and hydrological changes in tropical Africa during the past million years. Comptes Rendus Paleovol 5, 35–43.

Gasse, F., Barker, P., Gell, P.A., Fritz, S.C., Chalié, F., 1997. Diatom-inferred salinity in paleolakes: an indirect tracer of climate change. Quaternary Science Reviews 16, 547–563.

Gasse, F., Juggins, S., Ben Khelifa, L., 1995. Diatom-based transfer functions for inferring past hydrochemical characteristics of African lakes. Palaeogeography, Palaeoclimatology, Palaeoecology 117, 31–54.

Gasse, F., Chalié, F., Vincens, A., Williams, M.A.J., Williamson, D., 2008. Climatic patterns in equatorial and southern Africa from 30,000 to 10,000 years ago reconstructed from terrestrial and near-shore proxy data. Quaternary Science Reviews 27 (25–26), 2316–2340.

Gaudet, J.J., Melack, J.M., 1981. Major ion chemistry in a tropical lake basin. Freshwater Biology 11, 309–333.

Gawthorpe, R.L., Leeder, M.R., 2000. Tectono-sedimentary evolution of active extensional basins. Basin Research 12, 195–218.

Gowlett, J.A.J., Crompton, R.H., 1994. Kariandusi: Acheulean morphology and the question of allometry. The African Archaeological Review 12, 3–42.

Harwood, D.M., 1999. Diatomite. In: Stoermer, E.F., Smol, J.P. (Eds.), The Diatoms. University Press, Cambridge, pp. 436–443.

Hecky, R.E., Kilham, P., 1973. Diatoms in alkaline, saline lakes: ecology and geochemical implications. Limnology and Oceanography 18 (1), 53–71.

Hillaire-Marcel, C., Carro, O., Casanova, J., 1986. 14C and Th/U dating of Pleistocene and Holocene stromatolites from East African paleolakes. Quaternary Research 25, 312–329.

Hustedt, F., 1949. Süßwasserdiatomeen aus dem Albert-Nationalpark in Belgisch Kongo. In: Damas, H. (Ed.), Exploration du Parc National Albert (1935–1936). Hayez, Bruxelles.

Jätzold, R., 1981. Klimageographie – Ostafrika, Kenya, Uganda, Tanzania 2°N–2°S, 32–38°E. In: Freitag, U. (Ed.), Afrika-Kartenwerk, Serie E, Beiheft zu Blatt 5. Bornträger, Berlin.

Krammer, K., Lange-Bertalot, H., 1991a. Bacillariophyceae – 3. Teil: Centrales, Fragilariaceae, Eunotiaceae. In: Ettl, H., Gerloff, J., Heynig, H., Mollenhauer, D. (Eds.), Süßwasserflora von Mitteleuropa, vol. 2/3. Gustav Fischer, Stuttgart.

Krammer, K., Lange-Bertalot, H., 1991b. Bacillariophyceae – 4. Teil: Achnanthaceae, Kritische Ergänzungen zu Navicula (Lineolatae) und Gomphonema, Gesamtliteraturverzeichnis Teil 1–4. In: Ettl, H., Gerloff, J., Heynig, H., Mollenhauer, D. (Eds.), Süßwasserflora von Mitteleuropa, vol. 2/4. Gustav Fischer, Stuttgart.

Krammer, K., Lange-Bertalot, H., 1997a. Bacillariophyceae – 1. Teil: Naviculaceae. In: Ettl, H., Gerloff, J., Heynig, H., Mollenhauer, D. (Eds.), Süßwasserflora von Mitteleuropa, vol. 2/1. Gustav Fischer, Stuttgart.

Krammer, K., Lange-Bertalot, H., 1997b. Bacillariophyceae – 2. Teil: Bacillariaceae, Epithemiaceae, Surirellaceae. In: Ettl, H., Gerloff, J., Heynig, H., Mollenhauer, D. (Eds.), Süßwasserflora von Mitteleuropa, vol. 2/2. Gustav Fischer, Stuttgart.

Le Turdu, C., Tiercelin, J.-J., Gibert, E., Travi, Y., Lezzar, K.-E., Richert, J.-P., Massault, M., Gasse, F., Bonnefille, R., Decobert, M., Gensous, B., Jeudy, V., Tamrat, E., Mohammed, M.U., Martens, K., Atnafu, B., Chernet, T., Williamson, D., Taieb, M., 1999. The Ziway–Shala lake basin system, main Ethiopian Rift: influence of volcanism, tectonics, and climatic forcing on basin formation and sedimentation. Palaeogeography, Palaeoclimatology, Palaeoecology 150, 135–177.

Macdonald, R., Rogers, N.W., Fitton, J.G., Black, S., Smith, M., 2001. Plume–Lithosphere interaction in the generation of the basalts of the Kenya Rift, East Africa. Journal of Petrology 42 (5), 877–900.

McCall, G.J.H., Baker, B.H., Walsh, J., 1967. Late Tertiary and Quaternary sediments of the Kenya Rift Valley. In: Bishop, W.W., Clark, J.D. (Eds.), Background to Evolution in Africa. University of Chicago Press, pp. 191–220.

Milbrink, G., 1977. On the limnology of two alkaline lakes (Nakuru and Naivasha) in the East Rift Valley System in Kenya. Internationale Revue der Gesamten Hydrobiologie 62 (1), 1–17.

Ministry of Energy and Regional Development (MERD), 1987. Geologic Map/Geostructural Map/Geogravity Map of Kenya, Scale 1:1,000,000. Republic of Kenya, Nairobi.

Mortimer, E., Paton, D., Scholz, C., Strecker, M.R., Blisniuk, P., 2007. Orthogonal to oblique rifting: effect of rift basin orientation in the evolution of the North basin, Malawi Rift, East Africa. Basin Research 19, 393–407.

Nicholson, S.E., 1996. A review of climate dynamics and climate variability in Eastern Africa. In: Johnson, T.C., Odada, E. (Eds.), The Limnology, Climatology and Paleoclimatology of the East African Lakes, The International Decade for the East African Lakes (IDEAL). Gordon and Breach Publishers, pp. 25–56.

Owen, R.B., 2002. Sedimentological characteristics and origins of diatomaceous deposits in the East African Rift System. SEPM Special Publication 73, 233–246.

Partridge, T.C., DeMenocal, P.B., Lorentz, S.A., Paiker, M.J., Vogel, J.C., 1997. Orbital forcing of climate over South Africa: a 200,000-year rainfall record from the Pretoria Saltpan. Quaternary Science Reviews 16, 1125–1133.

Pik, R., Marty, B., Carigan, J., Yirgu, C., Ayalew, T., 2008. Timing of the East African development in southern Ethiopia: implication for mantle plume activity and evolution of topography. Geology 36, 167–170.

Richardson, J.L., Dussinger, R.A., 1986. Paleolimnology of mid-elevation lakes in the Kenya Rift Valley. Hydrobiologia 143, 167–174.

Richardson, J.L., Richardson, A.E., 1972. History of an African Rift Lake and its climate implications. Ecological Monographs 42, 499–534.

Ring, U., Schwartz, H., Bromage, T.G., Sanaane, C., 2005. Kinematic and sedimentological evolution of the Manyara Rift in northern Tanzania, East Africa. Geological Magazine 142 (4), 355–368.

Rodhe, H., Virji, H., 1976. Trends and periodicities in East African rainfall data. Monthly Weather Review 104, 307–315.

Roessner, S., Strecker, M., 1997. Late Cenozoic tectonics and denudation in the Central Kenya Rift: quantification of longterm denudation rates. Tectonophysics 278, 83–94.

Scholz, C.A., Johnson, T.C., Cohen, A.S., King, J.W., Peck, J.A., Overpeck, J.T., Talbot, M.R., Brown, E.T., Kalindekafe, L., Amoako, P.Y., Lyons, R.P., Shanahan, T.M., Castañeda, I.S., Heil, C.W., Forman, S.L., McHargue, L.R., Beuning, K.R., Gomez, J., Pierson, J., 2007. East African megadroughts between 135 and 75 thousand years ago and bearing on early-modern human origins. Proceedings of the National Academy of Sciences of the United States of America 104 (42), 16416–16421. 16.

Scott, S.C., Skilling, I.P., 1999. The role of tephrachronology in recognizing synchronous Caldera-forming events at the Quaternary colcanoes Longonot and Suswa, south Kenya Rift. Geological Society, London, Special Publications 161, 47–67.

Ségalen, L., Lee-Thorp, J.A., Cerling, T., 2007. Timing of C_4 grass expansion across sub-Saharan Africa. Journal of Human Evolution, 1–11.

Sepulchre, P., Ramstein, G., Fluteau, F., Schuster, M., Tiercelin, J.J., Brunet, M., 2006. Tectonic uplift and Eastern Africa aridification. Science 313, 1419–1423.

Smol, J.P., Birks, H.J.B., Last, W.M. (Eds.), 2001. Tracking Environmental Change Using Lake Sediments. Terrestrial, Algal and Siliceous Ondicators, vol. 3. Kluwer Academic Publishers, Dortrecht.
Stoffers, P., Hecky, R.E., 1978. Late Pleistocene–Holocene evolution of the Kivu–Tanganyika Basin. In: Matter, A., Tucker, M.E. (Eds.), Modern and Ancient Lake Sediments. Int. Assoc. Sed. Spec. Pub., vol. 2, pp. 43–55.
Strecker, M., Blisniuk, P., Eisbacher, G., 1990. Rotation of extension direction in the central Kenya Rift. Geology 18, 299–302.
Stuiver, M., Reimer, P.J., 1993. Extended ^{14}C data base and revised Calib. 3.0 ^{14}C age calibration program. Radiocarbon 35, 215–230.
Sturchio, N.C., Dunkley, P.N., Smith, M., 1993. Climate-driven variations in geothermal activity in the northern Kenya rift valley. Nature 362, 233–234.
Talling, J.F., Talling, I.B., 1965. The chemical composition of African lake waters. Internationale Revue Gesamten Hydrobiologie 50, 421–463.
Tiercelin, J.-J., Lezzar, K.-E., 2002. A 300 million years history of rift lakes in Central and East Africa: an updated broad review. In: Odada, E.O., Olago, D.O. (Eds.), The East African Great Lakes: Limnology, Paleolimnology and Biodiversity, 12. Advances in Global Change Research, pp. 3–60.
Trauth, M.H., Deino, A.L., Bergner, A.G.N., Strecker, M.R., 2003. East African climate change and orbital forcing during the last 175 kyr BP. Earth and Planetary Science Letters 206, 297–313.
Trauth, M.H., Maslin, M.A., Deino, A., Strecker, M.R., 2005. Late Cenozoic moisture history of East Africa. Science 309, 2051–2053.
Trauth, M.H., Maslin, M.A., Deino, A., Strecker, M.R., Bergner, A.G.N., Dühnforth, M., 2007. High- and low-latitude forcing of Plio-Pleistocene African climate and human evolution. Journal of Human Evolution 53 (5), 475–486.
Trauth, M.H., Larrasoaña, J.C., Mudelsee, M., 2009. Trends, rhythms and events in Plio-Pleistocene African climate. Quaternary Science Reviews 28, 399–411.
Verschuren, D., 1999. Sedimentation controls on the preservation and time resolution of climate-proxy records from shallow fluctuating lakes. Quaternary Science Reviews 18, 821–837.
Verschuren, D., Laird, K.R., Cumming, B.F., 2000. Rainfall and drought in equatorial Africa during the past 1100 years. Nature 403, 410–413.
Vincent, C.E., Davies, T.D., Beresford, A.K.C., 1979. Recent changes in the level of Lake Naivasha, Kenya, as an indicator of equatorial Westerlies over East Africa. Climatic Change 2, 175–189.
Vrba, E., Denton, G., Burckle, L., Partridge, T. (Eds.), 1995. Paleoclimate and Evolution with Emphasis on Human Origins. Yale Univ. Press, New Haven.
Washbourn-Kamau, C., 1970. Late Quaternary chronology of the Nakuru–Elmenteita Basin, Kenya. Nature 226, 253–254.
Washbourn-Kamau C.K., 1975. Late Quaternary shorelines of Lake Naivasha, Kenya. Azania, X, pp. 77–92.
Yielding, G., Roberts, A.M., 1992. Footwall uplift during normal faulting – implications for structural geometries in the North Sea. In: Larsen, R.M. (Ed.), Structural and Tectonic Modelling and Its Application to Petroleum Geology. NPF Special Publications, vol. 1, pp. 289–304.
Yuretich, R.F., 1982. Possible influences upon lake development in the East African Rift valleys. Journal of Geology 90, 329–337.
Yuretich, R.F., Ervin, C.R., 2002. Clay minerals as paleoenvironmental indicators in two large lakes of the African rift valley: lake Malawi and Lake Turkana. In: Renaut, R.W., Ashley, G.M. (Eds.), Sedimentation in Continental Rifts. SEPM Special Publications, vol. 73, pp. 221–232.
Zielke, O., Strecker, M.R., 2009. Recurrence of large earthquakes in magmatic continental rifts: insights from a paleoseismic study along the Laikipia-Marmanet fault, Subukia Valley, Kenya Rift. Bulletin of the Seismological Society of America 99 (1), 61–70.