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ORIGINAL PAPER

Seismic records of late Pleistocene aridity in Lake Tanganyika, tropical East Africa

Michael M. McGlue · Kiram E. Lezzar · Andrew S. Cohen · James M. Russell · Jean-Jacques Tiercelin · Anna A. Felton · Evelyne Mbede · Hudson H. Nkotagu

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Abstract New intermediate-resolution, normal-incidence seismic reflection profiles from Lake Tanganyika's central basin capture dramatic evidence of base-level change during two intervals of the late Pleistocene. Four seismically-defined stratigraphic sequences (A–D) tied to radiocarbon-dated sediment cores provide a chronology for fluctuating environmental conditions along the Kalya Platform. Stacked, oblique clinoforms in Sequence C are interpreted as prograding siliciclastic deltas deposited during a major regression that shifted the paleo-lake shore ~21 km towards the west prior to ~106 ka. The topset-to-foreset transitions in these deltas suggest lake level was reduced by ~435 m during the period of deposition. Mounded reflections in the overlying sequence are interpreted as the backstepping remnants of the delta system, deposited during the termination of the lowstand and the onset of transgressive conditions in the basin. The youngest depositional sequence reflects the onset of profundal sedimentation during the lake level highstand. High amplitude reflections and deeply incised channels suggest a short-lived desiccation event that reduced lake level by ~260 m, interpreted as a product of Last Glacial Maximum (32–14 ka) aridity. Paleobathymetric maps constructed for the two interpreted regressions reveal that despite the positive lake-floor topography created by the Kavala Island Ridge Accommodation Zone, Lake Tanganyika remained a large, mostly connected water body throughout the late Pleistocene. The results of this analysis further imply that Lake Tanganyika is the most drought resistant water body in the East African tropics, and may have acted as a refuge for local and migrating fauna during periods of prolonged aridity.

Keywords Lake Tanganyika · Lowstand · Paleolimnology · Rift-valley lake · Seismic stratigraphy · Tropical paleoclimate

M. M. McGlue (✉) · K. E. Lezzar · A. S. Cohen · A. A. Felton
Department of Geosciences, The University of Arizona, 1040 East Fourth Street, Tucson, AZ 85721, USA
e-mail: mmmcglue@email.arizona.edu

J. M. Russell
Department of Geological Sciences, Brown University, 342 Brook Street, Box 1846, Providence, RI 02912, USA

J.-J. Tiercelin
UMR 6118 Géosciences-Rennes CNRS, Université de Rennes1, Campus de Beaulieu, 35042 Rennes Cedex, France

E. Mbede · H. H. Nkotagu
Department of Geology, University of Dar es Salaam, Dar es Salaam, Tanzania

Introduction

Over the past several decades, paleolake level data from the Great Lakes of East Africa have been used to infer variability in the tropical climate system, serving as indicators for trends in effective precipitation (e.g., Street and Grove 1979; Kutzbach and Street-Perrott 1985; Johnson et al. 1996; Farrera et al. 1999). Large tectonic lake basins are a particularly important resource for understanding the response of the tropics to climatic flux, principally because of the unmatched spatial and temporal resolution of their sedimentary deposits. Cenozoic extension of the East African crust spurred the fortuitous evolution of deeply subsided lake basins fed by watersheds that, in some instances, span several degrees of latitude. These conditions are ideal for developing long (10^4–10^6 year) sedimentary records of both local and regional climate change for the African tropics. Moreover, profundal depositional environments found in the deepest of the rift lakes are rarely impacted by erosion (e.g., Johnson et al. 2002), thus avoiding the clipping of paleoenvironmental records during protracted periods of aridity. The key relationship that makes paleoenvironmental studies using data from East African rift lakes feasible is the interrelationship between effective precipitation, lake surface elevation, and basin sill height. Lake hydrology exerts a fundamental control on patterns of sediment accumulation and facies architecture in large lakes (Carroll and Bohacs 1999). Over relatively short intervals of geologic time (e.g., orbital frequencies; $\leq 10^5$ years), climate change appears to be a more persistent forcing mechanism on rift-lake basin hydrology than basin geodynamics or volcanism.

Recent breakthroughs in lake drilling notwithstanding (Koeberl et al. 2005; Scholz et al. 2006), most studies of African paleolake levels in extant lakes have been based on inferences made from relatively short sediment cores. Although a great wealth of knowledge has been derived from sediment core-based studies, certain limitations arise when evaluating base level dynamics exclusively from core data, especially on record duration imposed by the length of the coring device, and the indirect nature of lake level inferences derived from microfossils or geochemical data. In the absence of other corroborating data, establishing the magnitude of lake level change in large lakes using indirect records from sediment cores remains a challenge. The response of Lake Tanganyika to arid climatic conditions prevalent during the Last Glacial Maximum (LGM; ~32–14 ka) provides a pertinent example. Despite numerous investigations, the magnitude of lake level fall during the LGM has remained equivocal for decades. No fewer than thirteen sediment-core based analyses have been published on the subject, with interpreted estimates of lake level decline ranging from 150–600 m (e.g., Livingstone 1965; Hecky and Degens 1973; Haberyan and Hecky 1987; Tiercelin et al. 1989; Gasse et al. 1989; Tiercelin and Mondeguer 1991; Williamson et al. 1991; Vincens et al. 1993; Chalie 1995; Lezzar et al. 1996; Bergonzini et al. 1997; Cohen et al. 1997; Scholz et al. 2003). Quantifying the magnitude of regression events is important not only for quantitative paleoclimatology (e.g., Hastenrath and Kutzbach 1983), but also for considering the impact of bathymetric variability on ecological interactions and the tempo of speciation (e.g., Sturmbauer and Meyer 1992; Johnson et al. 1996; Verheyen et al. 2003).

One approach that can be adopted to aid lake level reconstructions is to combine the results of sediment core analyses with independent geomorphic evidence of paleo-shorelines. For example, hanging strandlines and wave cut terraces can be used to assess the extent of highstand conditions in a lake basin's history, when preserved materials permit age-dating. This technique has been widely employed to reconstruct lake level histories for sites around the world (e.g., Talbot and Delibrias 1980; Thompson 1992; Placzek et al. 2006). In the absence of subaerial evidence, sub-lacustrine geomorphologic features imaged with high frequency, marine-type seismic sources can also substantially improve lake level reconstruction efforts (e.g., Scholz 2001; D'Agostino et al. 2002; Anselmetti et al. 2006). Synthesizing seismically imaged evidence of paleo-shoreline position with sediment core analyses provides one of the most robust methods available to paleolimnologists for characterizing lake level history.

The goals of this study are to provide new insights on late Quaternary lake level change in Lake Tanganyika, central East Africa, using a grid of seismic profiles correlated with dated sediment cores. Several prior studies on Tanganyikan lake levels have used sediment core data in concert with observations from seismic profiles (Tiercelin et al. 1989; Mondeguer 1991; Scholz et al. 2003). Where seismic data have been extensively used, low line density, poor resolution and wide error bars associated with the "reflection seismic radiocarbon method" (RSRM) have permitted only minimum age estimates for Quaternary lake level fluctuations (e.g., Lezzar et al. 1996; Cohen et al. 1997). As a result, the full potential of seismic profiling for lake level reconstruction has not yet been realized on Lake Tanganyika. In this study, we collected a tight grid of intermediate-resolution seismic data in a region favorable for assessing the impact of climate on the stratigraphic record. We focused on developing a detailed seismic stratigraphic framework that is used to frame new arguments about the bathymetric impacts of two major regression events that affected Lake Tanganyika during the late Pleistocene. We place chronological constraints on our seismic interpretation through correlation with a growing database of well-dated sediment cores that were collected along the seismic grid, and to the north of our study area (Cohen et al. 2004; Felton et al. 2007; Scholz et al. 2007).

Description of study area

Lake Tanganyika and the Western Rift Valley

The formation of the Western Rift Valley of the East African Rift System (EARS) and its extant lakes has been traced to the middle Miocene (Cohen et al. 1993; Nyblade and Brazier 2002). Extensional deformation of the upper crust followed deep crustal heterogeneities and helped form a series of elongate rift basins, marked by high-angle, basin-bounding border faults (Morely 1989; Versfelt and Rosendahl 1989). Lake Tanganyika occupies several opposite polarity rift basins, and it is centrally located within the Western Rift Valley. The lake spans the international borders of four different nations: Tanzania, Zambia, Democratic Republic of the Congo and Burundi (Fig. 1).

Lake Tanganyika is the second largest lake on Earth by volume, reaching a maximum depth of ~1470 m in its southern basin (Capart 1952; Rosendahl et al. 1988). Due to its position relative to the equator, the lake and its surrounding environments experience a moist tropical climate, receiving an average of ~1200 mm of precipitation annually (Coulter and Spigel 1991). Patterns of rainfall in the region are affected by monsoon winds and the yearly migration of the Inter-tropical Convergence Zone (Nicholson 1996). Vegetation surrounding the lake is primarily Zambezian (seasonally-arid) woodlands, with Afromontane belts at higher elevations, reflecting the regional climate and local orographic effects (White 1983).

Lake Tanganyika is meromictic, with a seasonally well-mixed eplimnion and an anoxic hypolimnion below ~150 m (Hecky and Degens 1973). The lake is hydrologically open, draining to the west into the greater Congo basin through the Lukuga River (Fig. 1). The basin's sill depth is relatively shallow (<15 m), allowing the lake to become hydrologically closed with only minor drops in effective precipitation. At present, enriched surface water oxygen isotope values suggest that evaporation is the dominant process governing water loss from the lake (Craig et al. 1974; Dettman et al. 2005). Surface water chemistry and carbonate precipitation today are strongly influenced by exposures of Cenozoic volcanic rocks and hydrothermal inputs from Lake Kivu to the north (Haberyan and Hecky 1987; Felton et al. 2007).

The Kalya Platform

Our study was focused on the Kalya Platform, a westward dipping flexural margin of the East Marungu Half Graben, located in the central part of Lake Tanganyika, south of the Mahale Mountains (Fig. 2). The Kalya Platform is structurally linked to the Kalya Horst. Movement on normal faults has created an asymmetric, along-strike platform morphology, characterized by a steeper gradient in the north, which gradually diminishes to the south. In the dip direction, the platform morphology is that of a homoclinal ramp (Fig. 3). Several minor normal faults dissect the platform, but large faults creating significant stratigraphic separation were not imaged. Subsidence on the platform is relatively minor, due to flexural uplift associated with subsidence on the basin-bounding border fault (e.g., Lezzar et al. 2002). Data collection efforts were focused at this site because of its potential for an intact stratal record of paleo-shoreline position unobscured by steep canyons, deepwater bypass or pervasive mass wasting. In addition, the position of the seismic grid up-dip of the Kalya Horst allows for correlation with high-resolution sediment core records of late Pleistocene and Holocene climate

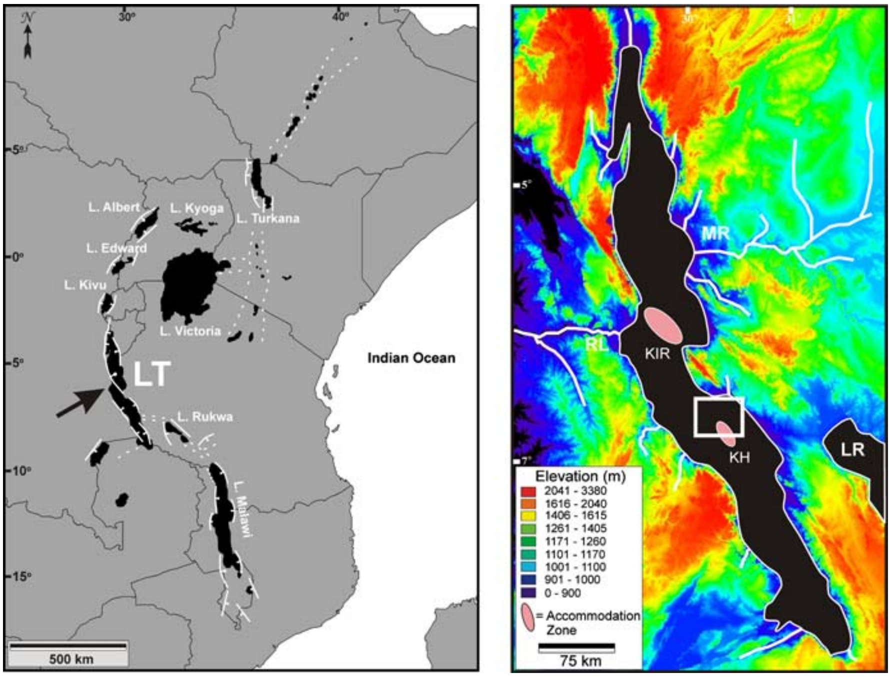

Fig. 1 Overview map of the EARS. An arrow marks the location of Lake Tanganyika (LT), northwest of Lake Malawi. Right-hand panel is a digital elevation model showing the full extent of the lake. Note the location of the Lukuga River (RL), the hydrological outlet for Lake Tanganyika. The region inside the box is the focus area of this study, presented in Fig. 2. The positions of the Kavala Island Ridge (KIR) and the Kalya Horst (KH) are marked by ovals. MR = Malagarasi River. LR = Lake Rukwa

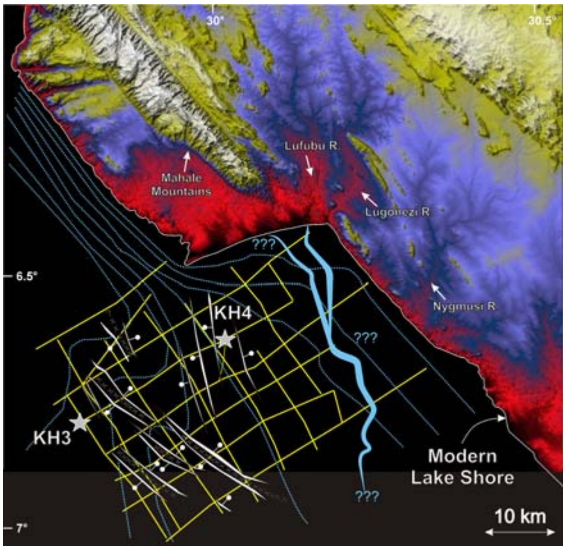

Fig. 2 Seismic trackline map for sparker profiles collected in 2004. The bathymetric contour interval is ~100 m. Stars mark core locations discussed in the text. Major basement ridges (heavy lines with XXX's) and faults appear as light grey lines; cherries mark the down-dropped hanging wall of the faults. Major rivers (Lufubu and Luginezi Rivers) enter the lake both orthogonally and obliquely. Although a complete understanding of the sub-aqueous channel system on the Kalya Platform awaits the collection of new seismic profiles, a tentative network based on observations from seismic dip lines is presented in blue. See text for details

change (Felton et al. 2007; Tierney and Russell 2007).

Methods

Acquisition and processing of seismic reflection profiles

Seismic reflection profiles used in this study were collected on Lake Tanganyika in 2004 in conjunction with the Nyanza Project research-training program. Kullenberg piston cores, described in detail elsewhere (Cohen et al. 2004; Felton et al. 2007) were collected along the seismic grid during the same field season (Fig. 2). Details of the field acquisition program, including source and receiver parameters, are summarized in Table 1. In all, more than 400 line km of digital, normal-incidence seismic data were available for the analysis. Data were collected in a grid pattern, with a mean line spacing of ~6 km (Fig. 2). The position of the seismic grid was oriented so that dip lines were orthogonal to the NW-SE axis of the half graben. Landmark Promax 2D® seismic processing software was used to enhance the signal-to-noise ratio of the data (Table 1). Where seismic time-to-depth conversions are made, we assume a

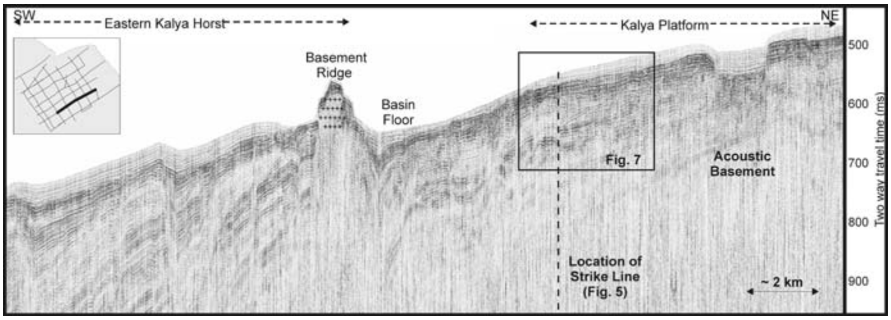

Fig. 3 A typical, southwest-northeast oriented seismic dip profile illustrating the gently sloping, ramp morphology of the Kalya Platform. Note that the vertical scale is in two way travel time (milliseconds). The basement-involved Kalya Horst marks the center of the line. An inset map (upper left corner) shows the relative position of the line on the seismic grid. The box defines the data shown in Fig. 10 and a dashed line marks the position of the crossing strike line in Fig. 5

Table 1 Seismic acquisition and processing parameters, Kalya Region, Lake Tanganyika

Source	SIG sparker
Source depth	1 m
Power	1000 J
Frequency	0–1500 Hz (producing vertical resolution <1 m)
Sampling rate	3000 Hz
Shot rate	2000 ms
Receiver	SIG six-channel streamer (towed 60 m from source)
Acquisition	DELPH digital acquisition system (1700 ms record length)
Navigation	Garmin GPS II
Processing	Bandpass filter, horizontal stack, top mute, AGC

velocity of 1450 m/s for the water column and uppermost sediments.

Stratigraphic and paleobathymetric interpretations

Following processing, data were transferred to Landmark Seisworks 2D® for interpretation. Our interpretation strategy focused on developing a detailed stratigraphic framework for the Kalya Platform using the principles of seismic sequence stratigraphy, especially as applied to lacustrine strata (Bohacs et al. 2000; Scholz 2001). Depositional geometries and unconformities are well expressed on the Kalya Platform, whereas stratal relationships in deepwater equivalents are dominantly conformable. On our seismic profiles, sequence boundaries were mapped as surfaces displaying onlap or truncation of reflections; these surfaces may be bound by flooding surfaces characterized by downlap. Interpretations from seismic reflection profiles were correlated to two sediment cores collected along our seismic grid: core KH3 and core KH4 (Fig. 2). Previously published age models for these cores, developed from AMS ^{14}C dates corrected for Lake Tanganyika's hard water effect, help place chronological constraints on the youngest sequence interpreted in the basin (Cohen et al. 2004; Felton et al. 2007). Paleo-bathymetric reconstructions were facilitated by compiling and digitizing modern water depth information (Capart 1952; Rosendahl et al. 1988) into a geographic information system. Volumetric calculations followed the geometric method discussed by Wetzel (2001).

Results

Seismic sequences

We identified four depositional sequences that can be mapped across the Kalya Platform, labeled Sequence D, C, B and A (from oldest to youngest, see Figs. 4 and 5). The depositional geometries in the oldest sequence are difficult to map with a high degree of confidence due to a decreased signal-to-noise ratio, caused in part by the inability of the high-frequency seismic source to penetrate great thicknesses of sediment.

Sequence D

Sequence D is the oldest stratigraphic sequence that can be interpreted in the dataset. This depositional

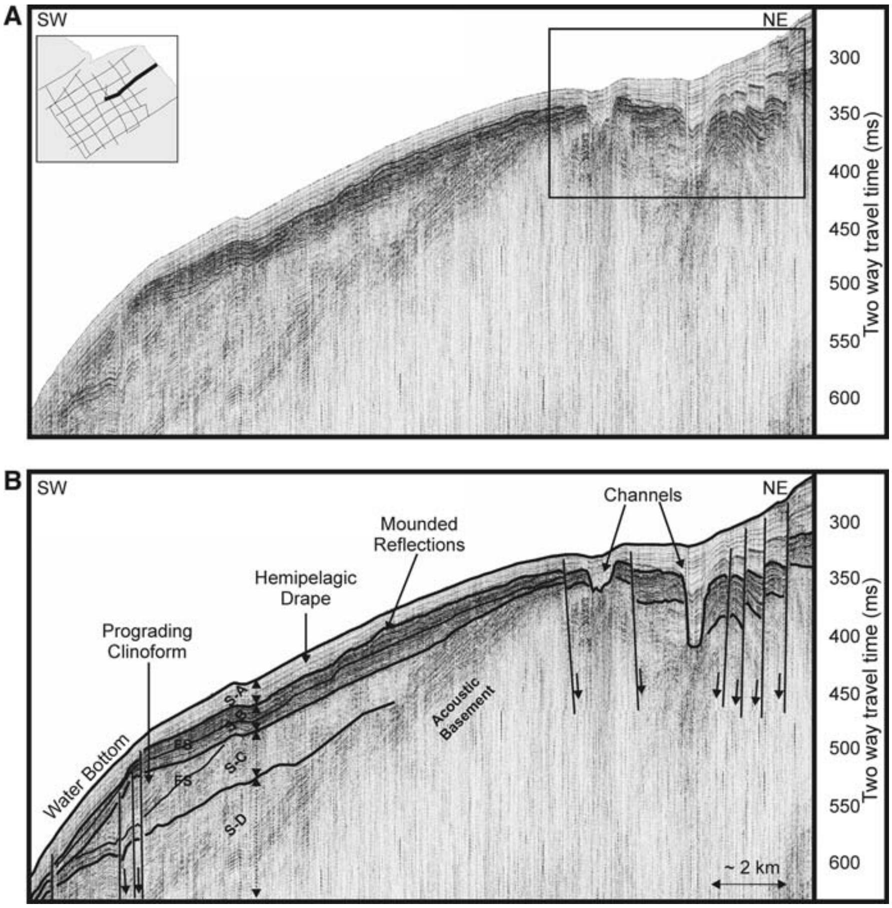

Fig. 4 Seismic dip profile (southwest–northeast) from the Kalya Platform (**a**) with stratigraphic interpretation (**b**). S-A = Sequence A. S-B = Sequence B. S-C = Sequence C. S-D = Sequence D. Line location marked on inset trackline map in upper panel; box marks data described in detail in Fig. 9. Platform margin oblique clinoform and pronounced up-dip angular unconformity are well expressed within Sequence C, indicative of low lake level conditions during the African mega-drought interval

package is best expressed in the center of the seismic grid, as acoustic penetration is lost as the section thickens approaching a major border fault to the southwest. In the center of the grid, Sequence D reaches a maximum thickness of ~90 ms two way travel time (TWTT). Sequence D has a wedge-shaped external geometry and it is comprised of low to moderate amplitude, semi-continuous to discontinuous reflections (Fig. 4). Most of the internal reflections that make up Sequence D are tilted and dip towards the southwest. These reflections terminate against overlying reflections near the base of Sequence C (Fig. 5). Along strike, reflections in Sequence D are locally chaotic or poorly defined.

Sequence C

Sequence C overlies Sequence D and displays highly variable reflection geometries across the Kalya Platform. The basal contact for Sequence C is defined by a high-angle stratigraphic discordance marked by reflection terminations (Fig. 5). The internal character of Sequence C varies with position on the platform. Down-dip, near the distal margin of the platform, a series of well-developed, westward prograding clinoforms mark the depositional sequence. Several discrete oblique clinoform bodies can be mapped, and they appear to stack within Sequence C (Fig. 4). The external form of these deposits varies from north to south on the Kalya Platform. To the north, foreset and bottom-set beds are steeply dipping, whereas equivalent reflections to the south are more gently inclined. Although clinoform morphology varies along the platform, in all cases dipping foreset reflections terminate against topset reflections, forming a toplap unconformity (Fig. 6). In addition, onlapping reflections are often encountered along the toes of distal foreset beds. Internally, clinoforms are made up of low amplitude,

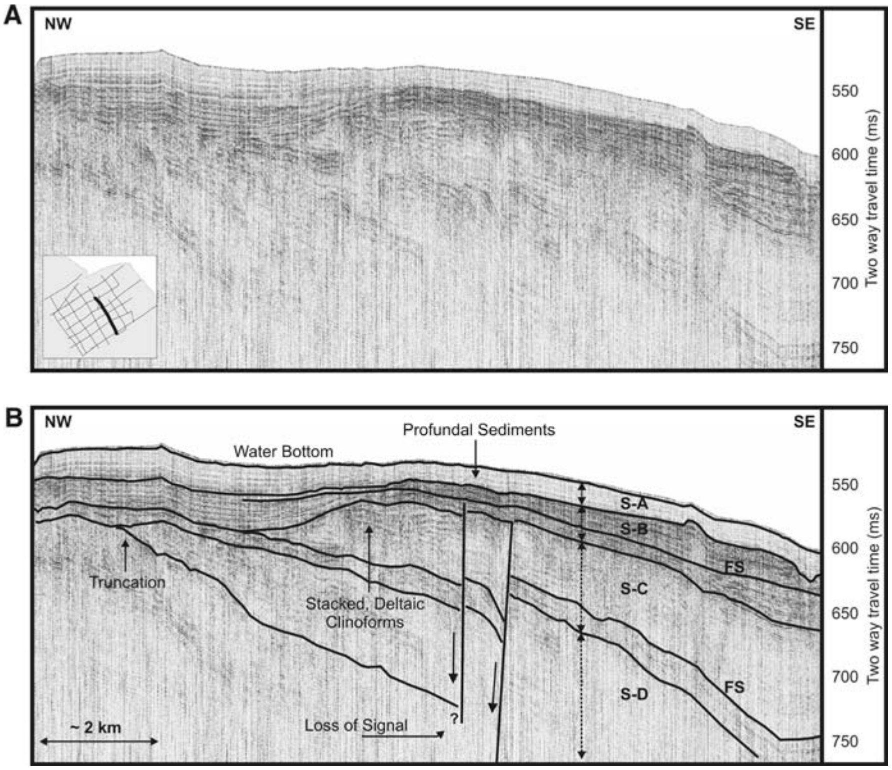

Fig. 5 Seismic strike profile (northwest-southeast) from the Kalya Platform (**a**) with stratigraphic interpretation (**b**). Line location marked on inset trackline map (upper panel). The wedge-shaped external form of Sequence D is evident, despite a loss of seismic signal deep in the section. Note the acoustically complex, stacked clinoforms within the overlying Sequence C. Stratigraphic sequences expand to the southeast due to increased accommodation space created by the Kalya Horst

semi-continuous reflections. The deepest clinoform in Sequence C occurs near the southern margin of the seismic grid, ~602 ms TWTT (~435 m) below the modern lake surface (Fig. 7). Other clinoforms in this sequence, located near the northern end of the platform, occur between 480 and 518 ms TWTT below the modern lake surface. Up-dip of the clinoforms, Sequence C exhibits several long, steeply dipping reflections that terminate against overlying Sequence B reflections in an angular unconformity near 370 ms TWTT (Fig. 5). The region between the clinoforms and the angular discordance is characterized by low amplitude, discontinuous seismic facies and by reflection-free seismic facies. In some instances, discontinuous reflections are concave up, producing local unconformities through the truncation of overlying reflections.

Sequence B

Sequence B can be traced throughout the study area, and it occupies the stratigraphic interval directly beneath Sequence A. The basal contact of Sequence B is readily identified by a high-angle stratigraphic discordance, where underlying, dipping reflections terminate against a set of overlying, flat-lying reflections (Fig. 5). Sequence B is commonly thicker than Sequence A, reaching an average thickness of ~35 ms TWTT. A strike line collected across the platform suggests a thickening of the sequence from north to south, as reflections diverge and locally onlap (Fig. 4). Sequence B is dominated by high-amplitude, semi-continuous, parallel seismic facies. Although this facies typifies the majority of the reflections in Sequence B, important variations do exist. In the center of the seismic grid, mound-shaped (concave down) reflections occur just above the basal contact, and appear to progressively back-step to a higher stratigraphic level within the sequence. Numerous reflection truncations characterize the internal structure of the mounds. In the strike direction, these mounds thicken the section, and form discrete lens-shaped packages of reflections (Fig. 8). These lenses are characterized by bi-directional downlap and internal reflection terminations. The local relief created by the mounds is minor, approaching 22 ms TWTT. These mounded

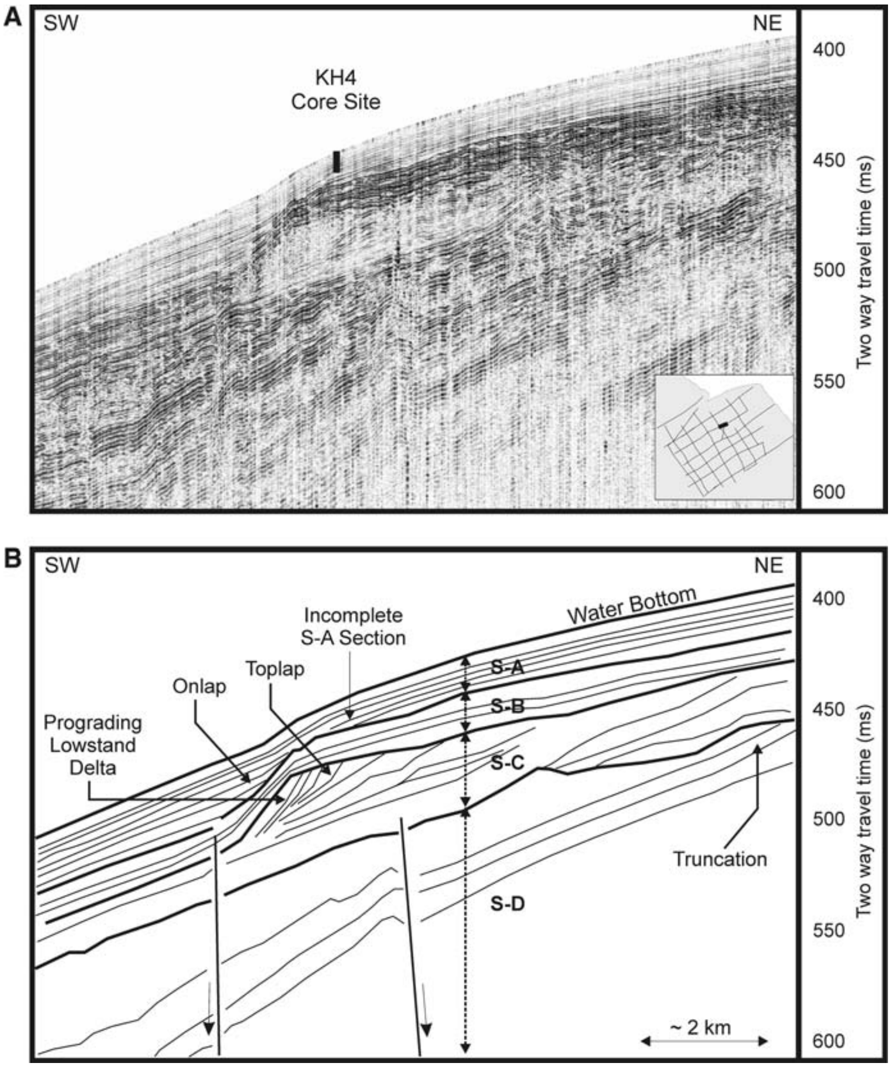

Fig. 6 Seismic detail (distal Kalya Platform) illustrating the clinoform morphology present in Sequence C and the location of sediment core KH4 (**a**) with interpretation (**b**). The facies contrast between the sequences interpreted in this study is pronounced in this locale. The stratigraphic section beneath the core site appears incomplete and Sequence A expands to the east. This reflection configuration implies age extrapolations made beneath the core site may underestimate the true age of the onset of profundal sedimentation following the African mega-drought interval. See text for details

reflections occur over an area of ~10 km^2, and are presently found ~410 ms TWTT below the modern lake surface.

Sequence A

Sequence A is the uppermost depositional package in the study area. The top of Sequence A is the modern sediment water interface. The basal contact of Sequence A is marked by onlapping reflections near the distal (western) margin of the platform, where the lake floor morphology changes from a homoclinal ramp to a steep slope at the platform-to-deep basin transition (Fig. 6). Sequence A reflections progressively terminate onto inclined underlying Sequence B reflections, forming an unconformable contact (Fig. 6). In areas where onlapping reflections are not found, Sequence A reflections display a drape geometry. The thickness of Sequence A typically varies between 16–24 ms (~12 to 17 m) across the Kalya Platform. The maximum observed thickness (~52 ms TWTT) occurs near the eastern limit of the seismic survey grid, where a series of pronounced channels create additional accommodation space near the lake bottom (Fig. 9). Sequence A is dominated by low amplitude, continuous, parallel seismic facies. These reflections extend over great distances, routinely exceeding 15 km. Whereas low amplitude continuous seismic facies characterizes the majority of Sequence A, a significant departure occurs

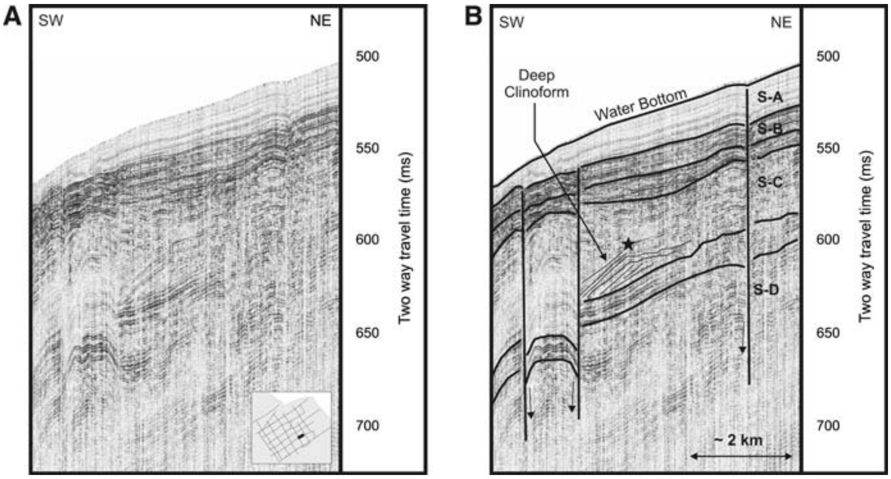

Fig. 7 Seismic detail of the buried clinoform used to define the magnitude of the lake level lowstand the occurred during Sequence C time. The bent appearance of reflections on the fault block adjacent to the clinoform (between the Sequence D boundary and the overlying flooding surface) result from deeper structures not shown in the image and a high degree of vertical exaggeration (>40×). Note that several topset reflections are eroded by an overlying channel, but the key topset-foreset transition is preserved (marked by a star on the right panel). Based on this reflection configuration, we suggest lake level was reduced by at least 435 m prior to 106 ka

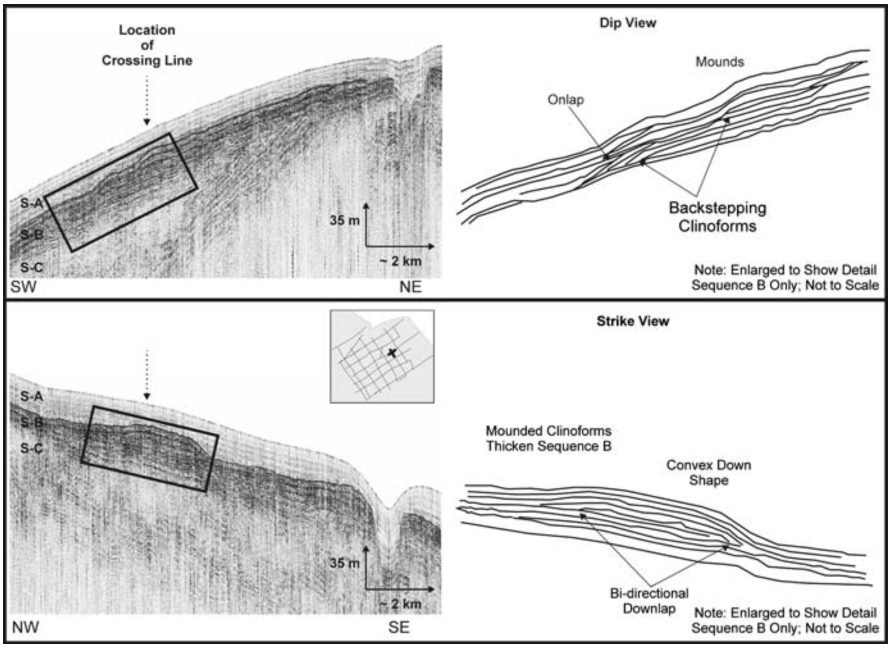

Fig. 8 Evidence of backstepping mounds in seismic sequence B. Seismic panels cross at the marked location, illustrating the cross-sectional geometry of a single mound. The backstepping mounds are spatially restricted, and thicken the section where they are present. Line drawings (right) illustrate the internal complexity of these deposits, which are interpreted as the transgressive remnants of the major lowstand delta system in Sequence C

on seismic lines that extend to within a few kilometers of the eastern shoreline. In this more proximal setting, low amplitude reflections are interrupted by a high amplitude, high frequency, two-cycle, reflection event (HARE) above 350 ms TWTT (Fig. 9). These continuous, parallel reflections grade down-dip into several channels, and they do not appear in the section deeper than ∼360 ms TWTT. The geometry of Sequence A reflections is likewise altered by the channels themselves. The channels create minor

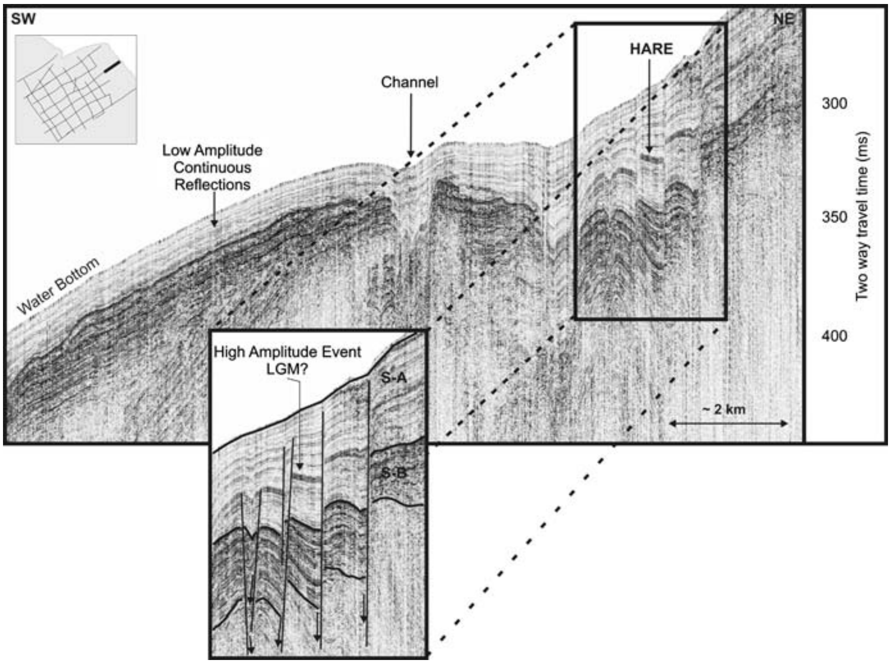

Fig. 9 Seismic detail (see Fig. 4 for line location) of the high amplitude reflection event (HARE) observed along the proximal (nearshore) portion of the Kalya Platform. Note the strong seismic facies contrast between these reflections and the low amplitude continuous reflections typical of Sequence A. The line also illustrates the additional accommodation space created by a set of young channels that traverse the platform from northwest to southeast. The law of cross cutting relationships suggests the channels have been recently active, and may reflect increased incision during the LGM low lake stand

negative relief on the lake bottom and they incise into the underlying reflections of Sequences B and C (Fig. 10). Reflections within the channels are truncated and variable. Seismic facies in the channels ranges from low amplitude to high-amplitude continuous to chaotic.

Sediment cores from Sequence A

Two Kullenberg piston cores were retrieved from Sequence A. Core KH3 was collected in ~600 m of water on the western side of the Kalya Horst. The core (7.75 m long) penetrated to ~6 m above the base of Sequence A. The core is dominated by profundal lithofacies (organic-rich ooze and clay) and has a basal age of ~60 ka (Fig. 11). A full account of the core's geochronology and sedimentology has been presented elsewhere (Felton et al. 2007). Sedimentation rates over the time period encompassed by the core range between 0.085–0.224 mm/year. Core KH4 was collected in ~330 m of water on the distal margin of the Kalya Platform (Cohen et al. 2004). This core is 7.29 m long, is likewise dominated by profundal lithofacies, with a basal age of ~41 ka (Fig. 11). The sedimentation rates for core KH4 vary between 0.175 and 0.231 mm/year based on available radiocarbon data.

Discussion

Seismic evidence of lake level change

The sequence stratigraphic framework (Sequences D through A) we have developed for the Kalya platform provides a relative chronological context for interpreting the region's paleo-environmental history. Depositional processes control reflection geometries and seismic facies characteristics, with stratal continuity, impedance contrast and bed spacing contributing to a lesser extent (Mitchum et al. 1977). As such, the vertical variability observed on our seismic profiles implies significant changes in the mode of deposition over the late Pleistocene along the Kalya Platform.

An accurate interpretation of the paleo-environment during Sequence D time is challenging given the limited resolution of this depositional package in our dataset. The wedge-shaped external form of Sequence D is common for hanging wall stratigraphic sequences in extensional basins, due to increased accommodation spaced created adjacent to major structures (Morley 1989; Schlische and Olsen 1990). The most defining characteristic of Sequence D is its angular, truncated reflections and low-to-moderate amplitude seismic facies. Lake level change is a routinely invoked

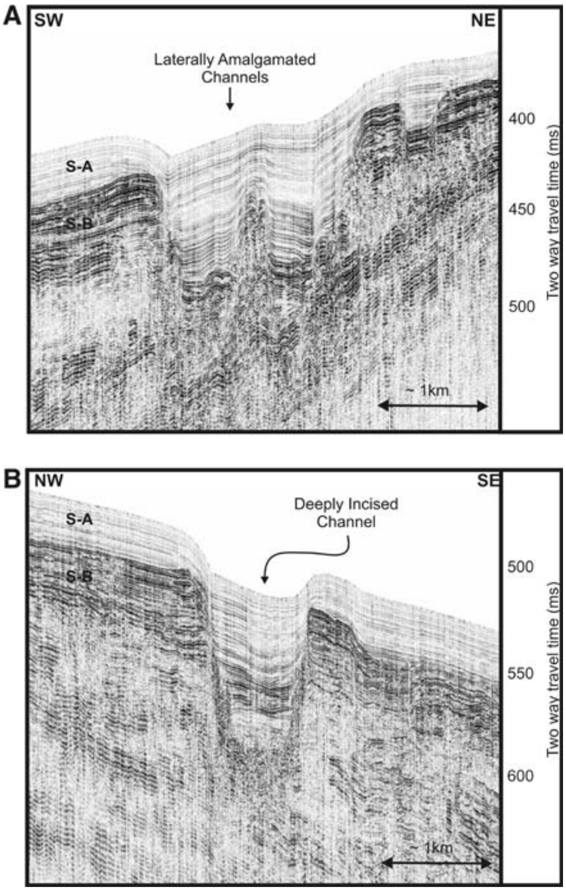

Fig. 10 Typical sub-lacustrine channels encountered on the Kalya Platform. Channels are shallow and narrow near the northern margin of the study area, and tend to deepen and laterally amalgamate near the southern terminus of the seismic grid (as in panel A). Offset of the lake bottom reflection, dominance of low amplitude continuous fill and cross cutting relationships indicate a recent period of channel downcutting. See text for discussion

mechanism for the origin of angular unconformities such as those that mark Sequence D (e.g., Scholz and Rosendahl 1988). The angular stratigraphic discordance in Sequence D, coupled with highly variable seismic facies characteristics, suggest this package may have been deposited during a lake level lowstand that exposed the entirety of the Kalya platform. However, because the tilting and truncation of Sequence D reflections may reflect the influence of tectonics, the paleo-environment during the deposition of Sequence D remains equivocal. Growth strata are generally under-reported in lake-basin studies, but Soreghan et al. (1999) noted the importance of uplift and rotation on footwall blocks on the development of canyons and acoustically complex coarse-grained deposits in Lake Malawi. In addition, a growing body of research suggests that syn-deformational unconformities may be pervasive in tectonically active basins (Riba 1976; Anadón et al. 1986; Hardy and McClay 1999). Gawthorpe et al. (1997), using examples from the Suez Rift, demonstrated that the geometry of rift-basin sequences can be strongly impacted by the vertical movement on buried normal faults. Whereas our seismic system is not suited to the imaging of deep structures, previous research using multichannel seismic analyses has led to the development of detailed fault maps for Lake Tanganyika (e.g., Rosendahl et al. 1988; Versfelt and Rosendahl 1989). Versfelt and Rosendahl (1989: Fig. 2) present a structural map that shows a large, down-to-the-southwest normal fault that occupies a position east of our seismic grid. Given the presence of this normal fault, we cannot rule out the possibility of a purely tectonic origin for the reflection configuration in Sequence D.

Sequence C reflects deposition during a period of significantly reduced lake level. The strongest evidence for lowstand conditions in this sequence are the platform-margin clinoforms coupled with a pronounced up-dip angular unconformity (Fig. 5). During the interval when these clinoforms developed the lake's shoreline would have been shifted by ~21 km to the west of its current location. Clinoform development in rift basins often correlates with a basinward shift of flexural margin river systems during subaerial exposure of the platform (Scholz 1995). Consequently, we interpret the platform-margin clinoforms in Sequence C as westward prograding, siliciclastic lowstand delta deposits. There is a rich body of literature from lacustrine settings that documents clinoform-shaped deltas, extending back to the work of Gilbert (1890) on paleo Lake Bonneville. In rift-lake basins, seismic studies have identified flexural margin clinoforms similar to those we observe in our dataset in both Lakes Malawi and Edward (Scholz 1995; McGlue et al. 2006).

Oblique clinoforms on the Kalya Platform are typified by shingled internal reflections and top truncation of foreset reflections (Fig. 6). Inclined foreset reflections mark the construction of the delta front at the lakeshore. Toplap forms through active sediment bypass indicative of a high-energy

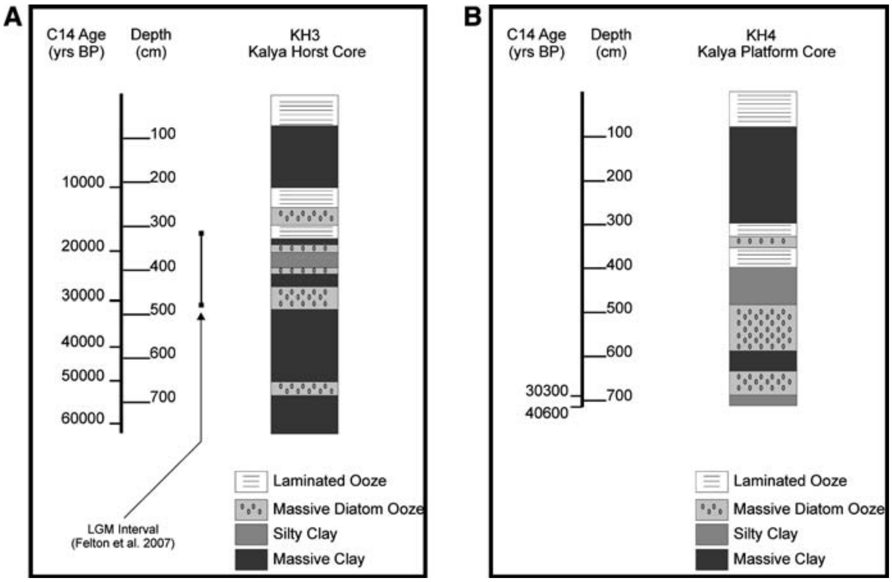

Fig. 11 Lithostratigraphy and geochronology (AMS 14C; see Cohen et al. 2004 and Felton et al. 2007) for sediment cores KH3 (A) and KH4 (B). Profundal sediments (organic rich silt and clay) dominate in the cores, suggesting deposition primarily by suspension fall-out. Sedimentation rates from these cores were used to estimate the onset of Sequence A sedimentation, marked by the return to a deep lake environment following a major regression prior to 106 ka

depositional environment without vertical accommodation space. Such an environment would have existed in Lake Tanganyika if lake level was much reduced; exposure of the platform to subaerial processes would allow for appreciable erosion and sediment bypass down-dip. The topset-to-foreset transition of the clinoforms is a useful geomorphic indicator that marks the relative position of lake level during Sequence C time (Burbank and Anderson 2001). Clinoforms on the Kalya Platform are stacked (a common phenomenon typically attributed to delta-lobe switching), such that the oldest deposits are found at the lowest stratal level. In our dataset, the deepest clinoform occurs near the southern terminus of the platform (Fig. 7). Although several minor normal faults impact the stratigraphic section, overall this region of the Kalya Platform displays a low gradient. As a consequence, lake level interpretations made from these deposits can be made with greater confidence than those to the north, which are being uplifted in the footwalls of several N-NNE trending platform faults. Using these criteria, we interpret lake level during Sequence C time to have been at least 436 m below the modern lake surface. The deepest clinoform appears to have been partially eroded by a channel that truncated the top of the feature, but nevertheless the offlap break is clear on our seismic profiles (Fig. 7). East of the clinoforms, a large angular unconformity reflects exposure of the platform updip of the lowstand delta. Reflections between the updip unconformity and the downdip clinoforms are discontinuous and in some locales, concave up. We interpret this seismic response as distributary channels along a delta plain environment.

We interpret Sequence B as a terminal lowstand to early transgressive period in the basin following the major regression in Sequence C. Sequence B reflections are high-amplitude and semi-continuous, suggesting a different depositional environment from that which prevailed during Sequence C time. We interpret Sequence B reflections as sediments deposited in a variety of near-shore environments, ranging from exposed lake margin to the submerged littoral zone. Perhaps the most striking evidence of the onset of transgressive conditions during Sequence B time comes from three mound-shaped reflection sets that back step to progressively higher stratigraphic levels within the sequence. These mounds contain numerous internal reflection terminations, and onlapping reflections from the west (Fig. 8).

Numerous mechanisms exist for the formation of mound-shaped seismic reflections, ranging from contrasting depositional processes to differential compaction (e.g., Mitchum et al. 1977), but three explanations are plausible in this case. The position of the mounds directly up-dip of the Sequence C clinoforms suggests that these reflections may record retrogradational deltaic sedimentation. Transgressive deltaic deposits have been encountered in marine shelf sequences (e.g., Yoo and Park 2000; Porebski and Steel 2006) but they have not previously been reported from East Africa. The apparent lack of transgressive deltaic deposits in African rift lakes can be explained by a number of factors, including: (1) rapid rise of lake level following major regressions, trapping the fluvial system close to the hinterland; (2) high wave energy during periods of lake level rise, leading to poor preservation of the backstepping delta or (3) spatial aliasing in wide seismic grids. We favor a deltaic interpretation due to the scale and internal complexity of these deposits. However, we cannot rule out the possibilities that the mounds in Sequence B represent shallow water carbonates or remnants of a barrier island system. Lake Tanganyika is renowned for its diversity of modern nearshore carbonates, including stromatolite banks and ooid build-ups (Cohen and Thouin 1987). Modern stromatolites in the lake are present down to ~40 m below the lake surface, whereas ooid shoals in both modern Lake Tanganyika and paleolake examples form at littoral depths (Swirydczuk et al. 1980; Cohen and Thouin 1987). Barrier island systems are not present in Lake Tanganyika today, but they have been documented in ancient lake systems characterized by high-energy coastlines (e.g., Adams and Wesnousky 1998). Regardless of a siliciclastic or carbonate origin, the presence of these deposits implies a shallow sub-aqueous paleoenvironment during Sequence B time, at least down-dip of the mounds.

We interpret Sequence A to reflect the onset of hemipelagic sedimentation in a profundal depositional environment. The low-amplitude, continuous seismic facies that distinguishes Sequence A from underlying reflections is typical of deepwater deposits in Lake Tanganyika (Tiercelin et al. 1989; Lezzar et al. 1996). The dominance of diatomaceous ooze and clay in the sediment cores collected from this sequence confirms that sedimentation was dominated by suspension fall-out of organic-rich material from the lake's epilimnion. Laterally continuous reflections, coupled with a long mean reflection length (>15 km), support the notion that widespread deep-water conditions prevailed during most of Sequence A time. Given the asymmetric morphology of the basin, the Kalya Platform lagged the Kalya Horst environment in its return to a profundal environment, as evidenced by the progressive onlap of low-amplitude continuous reflections from the west onto the toe of the distal platform (Fig. 6).

The only remarkable internal variability within Sequence A occurs near the eastern margin of the study area, where we observe a prominent HARE embedded within more typical low amplitude reflections ~24 ms TWTT below the lake floor (Fig. 9). In some instances, prominent reflections of this kind simply reflect predictable lateral facies variations, such as the progression of littoral sand bodies into fine-grained deposits of the profundal zone. However, we interpret this HARE as evidence for a smaller fluctuation in lake level during Sequence A time than what is observed earlier in the record. High-frequency base level fluctuations induced by climate change are common in tropical lakes and Lake Tanganyika is no exception. Numerous analyses of sedimentary indicator materials have suggested that changes in effective moisture have altered the lake's surface elevation and forced hydrologic closure in the recent past (e.g., Haberyan and Hecky 1987; Alin and Cohen 2003). The strong impedance contrast between the low amplitude, continuous facies and the HARE suggests a density change in the sediments that comprise them; desiccated lake sediments, hardened by subaerial exposure and evaporation of interstitial pore fluids, is one possible means of creating this seismic response. Because the HARE is only observed above 350 ms TWTT, we interpret that lake level was reduced by a maximum of ~260 m during this short-lived event. Through correlation to previously published sediment core records, we suggest this event corresponds to the LGM, an interval of known tropical aridity caused by high-latitude glaciation (Gasse 2000). Trace elements and sedimentary organic matter analysis suggests that climatic conditions consistent with tropical aridity associated with the LGM persisted in Lake Tanganyika between about 32 and 14 ka (Felton et al. 2007). Notably, the LGM interval spans ~0.8 m in the KH3 sediment core record. For that reason, resolving the LGM in seismic records in regions that remained sub-aqueous is probably not possible due to the tuning effect produced by a source frequency at or below ~1 kHz. Consequently, a seismic stratigraphic manifestation of this global climate event can only be found where the lake bottom was exposed, which we interpret to be in areas where the modern water depth is less than ~260 m. An interesting feature in our seismic dataset is the spatial relationship between the incised channels that transverse the platform and the HARE we interpret as evidence of the LGM. The law of cross cutting relationships demands that the channels we observe are young features, formed late in Sequence A time based on the displacement of reflections by channel incision near the modern water bottom (Fig. 10). Channel formation can occur during lake level highstands through localized faulting, large-scale tilting that increases stream power, or through the activity of turbidity currents (e.g., Soreghan et al. 1999). Likewise, channels can incise during lake level lowstands due to exposure and down-cutting. A number of minor normal faults flank the channel margins in our data, suggesting a tectonic origin (Fig. 9). However, the stratigraphic separation on these faults is relatively minor, whereas the channels incise an average of ~40 ms into underlying strata. Therefore, we interpret the channels to be dominantly climatic in origin, likely associated with the LGM.

Geochronology of lowstand events

The transition to Sequence A

We can trace the timing of the onset of relative highstand conditions using sedimentation rates derived from our sediment cores. Felton et al. (2007) report a basal age for core KH3 of ~60 ka. The age model developed by these authors suggests that the sedimentation rate over this time interval varies, with an average approaching 0.13 mm/year. By extrapolating this sedimentation rate to the basal contact of Sequence A near the Kalya Horst, we estimate an age of ~106 ka for the onset of deposition. At the KH4 site, the age model presented in Cohen et al. (2004) implies an average sedimentation rate approaching 0.20 mm/year. Extrapolation of this rate from the lake bottom the sequence boundary suggests profundal sedimentation commenced ~55 ka at this site. Due to the variable nature of sedimentation in large lakes, age determinations developed through extrapolation must be made with caution. In the case of core KH3, the extrapolated age is bolstered by the similarity in seismic response both above and below the cored interval (Felton et al. 2007). Because depositional processes principally control seismic facies, we can be confident that similar sediments prevail beneath the cored interval of Sequence A at the KH3 site.

The chronology from core KH4 is somewhat more challenging to interpret, given the location of the coring site at the edge of the Kalya Platform. The seismic stratigraphic section beneath the core appears to be incomplete, due to the complex topography created by an underlying, uplifted delta lobe (Fig. 6). Moving up-dip from platform edge, the section thickens to 18–21 ms (TWTT) along most of the seismic grid; in these locales, the range of time encompassed by Sequence A expands to ~89–103 ka on the platform. This suggests that the age-extrapolation made from the KH4 core site probably underestimates the timing of the stratigraphic transition from Sequence B to Sequence A. Likewise, sub-seismic scale hiatuses in the KH4 record are suggested by the core's lithostratigraphy and may further contribute to underestimating the onset of Sequence A sedimentation. However, given the bathymetric contrast between the KH3 (~600 m) and KH4 (~330 m) sites, we can be certain of a time lag between transgression in the deepwater horst and flexural platform environments. This inference is confirmed by onlapping reflections moving up the platform margin from the west (Figs. 5 and 6). As a result, we suggest that the major transgression associated with the deposition of Sequence A triggered sedimentation at the KH3 site by ~106 ka, and followed thereafter at the KH4 site.

Regional evidence from the Kavala Island Ridge (Scholz et al. 2003), Lake Malawi (Cohen et al. 2007; Scholz et al. 2007) and northern Lake Tanganyika (Lezzar et al. 1996) helps address the timing of lowstand sedimentation along the Kalya Platform. Scholz et al. (2007) report a major transgression near the crest of the Kavala Island Ridge at ~97 ka, based on estimates from optically-stimulated luminescence dating. These authors suggest that the lowstand preceding this transgression (−393 m below modern) was an orbitally-forced mega-drought interval that severely impacted the African tropics. In Lake Malawi, a series of mega-droughts occurred between 135 and 70 ka (Scholz et al. 2007). We suggest that maximum lowstand conditions on the Kalya Platform occurred during this same interval. While we cannot directly determine the amount of time encompassed by Sequences B and C, the KH3 chronology suggests that lowstand deltaic deposition on the Kalya

Platform occurred prior to 106 ka. This chronology is broadly consistent with the observations from both the Kavala Island Ridge and Lake Malawi. Correlation with prior seismic results from the Bujumbura and Mpulungu Basins suggests that the "a" discontinuity (Lezzar et al. 1996; Cohen et al. 1997) and the "A" event (e.g., Tiercelin et al. 1989) in northern and southern Tanganyika, respectively are coeval with the base of Sequence A. Using the more precise KH3 chronology, we suggest that the time content of Sequence A is appreciably greater than the ~35.3–39.7 ka inferred from RSRM calculations of Lezzar and colleagues (1996). The reasoning behind this mismatch likely lies in assumptions inherent to the RSRM method regarding the relationship between sedimentation rates and acoustic facies characteristics.

The deltaic clinoforms in Sequence C allow for the first quantitative estimate of paleo-lake shore position for Lake Tanganyika. Prior research has suggested a sub-aerial exposure surface indicative of a regression event that lowered lake level by more than 600 m (Scholz and Rosendahl 1988; Cohen et al. 1997). However, the non-unique origin of angular unconformities in extensional basins, used to infer precise low lake stands in these earlier studies, and present in Sequence D, precludes a definitive identification of lake levels from Sequence D.

Evidence of the LGM in Sequence A

The HARE occurs, on average, 24 ms TWTT below the modern lake bottom near the eastern shore (Fig. 9). Assuming a velocity of 1450 m/s in the uppermost sediments of Sequence A, we estimate the accumulation of ~17.4 m of sediment since the termination of the LGM. Felton et al. (2007) suggest that glacial aridity ceased in the region around 14 ka. Therefore, we estimate that sedimentation rates close to shore since the termination of the LGM have been appreciably higher than those near the distal platform margin. Assuming the cessation of LGM aridity occurred at 14 ka, we derive a sedimentation rate for the proximal, nearshore component of Sequence A above the HARE of 0.12 cm/year. This estimate agrees well with littoral/deltaic sedimentation rate measurements presented by McKee et al. (2005), and provides a tentative explanation for the increased thickness of Sequence A along the eastern margin of the seismic grid.

The magnitude of lake level lowering in Tanganyika during the LGM has been a subject of considerable debate for several decades. Seismic evidence from the present study bears a strong resemblance to high-amplitude reflections discovered in echosounder records from the Bujumbura basin (Bouroullec et al. 1991; Lezzar et al. 1996). Sediment cores that penetrated the high amplitude "C_2" reflections, dated at ~23 ka, were composed of fine-grained sand to clayey-sand with mud balls (Lezzar et al. 1996). Cohen et al. (1997) suggested that the lowstand implied by these features reduced lake level by ~160 m, desiccating the Bay of Burton. Our new estimates confirm this paleogeographic scenario, but expand the magnitude of the regression by nearly 40%. Other studies have attempted to quantify water levels during the LGM using diatoms (see Gasse 2000; Scholz et al. 2003), as direct sedimentological evidence of desiccation has not been recovered. Our estimate for the magnitude of the LGM regression falls closest to the range reported in Gasse (<300 m; 2000) developed from planktonic/epiphytic diatoms.

Paleobathymetric reconstruction and implications

Based on our estimated lake levels for the key sequences discussed here we have constructed a series of paleobathymetric maps for Lake Tanganyika (Fig. 12). A geometric analysis of available bathymetric data reveals that the modern volume of Lake Tanganyika is ~19,690 km^3, about 3.0% larger than values regularly encountered in the literature. During the LGM (late Sequence A), the volume of Lake Tanganyika was reduced to ~12,800 km^3. During the African mega-drought interval (Sequence C), the volume of Lake Tanganyika was reduced to ~11,240 km^3, ~43% less than the modern.

Our seismic evidence suggests that the lake did not split into smaller, disconnected pools during the major Upper Pleistocene regression event of Sequence C. Close examination of multichannel seismic data collected in the 1980s reveals that the most likely locus for a significant separation occurs at the Kavala Island Ridge, in the center of the lake (Fig. 1). The crest of the Kavala Island Ridge creates a pronounced bathymetric high ~360 m below the

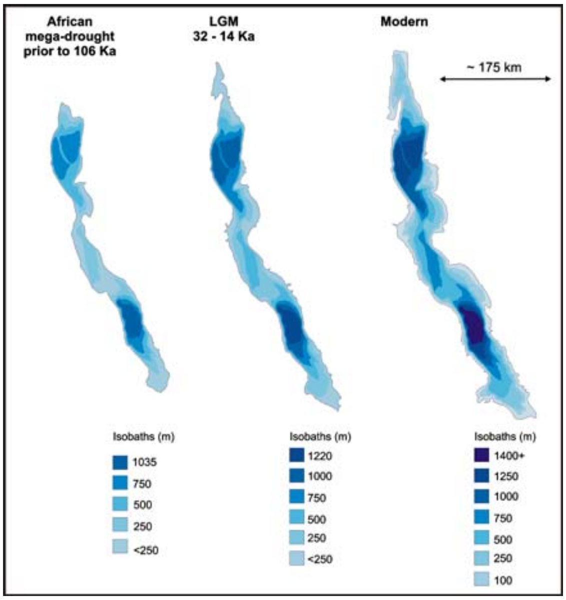

Fig. 12 Bathymetric maps for Lake Tanganyika, tropical East Africa for the African mega-drought period, prior to 106 ka; the Last Glacial Maximum (32–14 ka) and modern. Note that the lake remains a large, mostly connected water body in spite of these Pleistocene regression events

lake surface (Scholz et al. 2003). Evidence from top-truncated seismic reflections and sediment bulk density profiles supports the interpretation that the crest of the KIR is exposed during major regression events (Scholz et al. 2003; Scholz et al. 2007). However, the KIR is an asymmetric feature and the region west of the structural crest lies in water exceeding ~580 m. Paleobathymetric reconstructions created from this study show the lake would have remained connected during both the LGM and the African mega-drought interval. Unlike many other rift lakes, most of Lake Tanganyika's volume is contained below the 500-m isobath, perhaps due to the lake's great antiquity and a longer time period of subsidence on half-graben bounding border faults. As a result, Lake Tanganyika is the most drought-resistant water body in the Western Rift Valley, and likely the only standing water body in East Africa that would have persisted as a very deep lake during the mega-drought interval. Consequently, the lake may have been an important refuge for drought-intolerant fauna during intense periods of Quaternary aridity, and served as an important watering hole for local and migrating fauna throughout these climatic crises.

Conclusions

The results of this integrated assessment of the Kalya Platform's stratigraphy yield new insights on the magnitude of two major regressions that affected Lake Tanganyika during the late Quaternary. Whereas both the LGM and African mega-drought regressions forced significant lake level decline, only the earlier event strongly impacted the Platform's stratigraphic record. We suggest this reflects both the magnitude and the duration of Upper Pleistocene tropical aridity (~106 ka).

1. We interpret four stratigraphic sequences on the Kalya Platform. The origin of the oldest sequence (Sequence D) remains equivocal due to a lack of penetration and resolution in the deeper stratigraphic section.
2. Stacked, oblique clinoforms within Sequence C are interpreted as prograding lowstand delta deposits. Using the topset-to-foreset transition of the deepest delta lobe at the southern end of the Kalya Platform, we interpret that lake level was reduced by at least 435 m during the deposition of this deposit. Delta lobes at the northern end of the Kalya Platform within this sequence underestimate the magnitude of lake level change due to footwall uplift on active normal faults.
3. Sequence B records the end of lowstand conditions in the basin and the onset of rising water levels following the Sequence C drought. Mounded reflections within this sequence are interpreted as retrogradational backstepping deltaic deposits, marking the littoral—supra–littoral boundary during the time interval of deposition.
4. Sequence A records the return of the basin to highstand conditions, where profundal depositional processes dominate the section. The onset of profundal sedimentation, based on extrapolations from sediment cores, commenced by ~106 ka in the deep basin and shortly thereafter on the platform. A major departure from the low amplitude continuous seismic facies that characterizes the majority of Sequence A occurs near the eastern lake shore, where a high amplitude, two-cycle reflection marks the section above 350 ms TWTT, up-dip of highly incised channels. We interpret this facies change to mark the

short-lived LGM climatic event. The stratigraphic position of this high-amplitude reflection implies that lake level was reduced by ~260 m during this regression.

5. Paleo-bathymetric reconstructions for the Pan-African "mega-drought" period and the LGM (32–14 ka) suggest that Lake Tanganyika remained a large, contiguous water body despite significant, basinwide lake level decline. Due to its age and border fault configuration, it seems likely that Lake Tanganyika was the only large water body marking the East African landscape during the African megadrought interval. If correct, this interpretation has implications for the survival of local and regional fauna during episodes of extreme drought.

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References

Adams KD, Wesnousky SG (1998) Shoreline processes and the age of the Lake Lahontan highstand in the Jessup embayment, Nevada. Geol Soc Am Bull 110:1318–1332

Alin SR, Cohen AS (2003) Lake-level history of Lake Tanganyika, East Africa, for the past 2500 years based on ostracode-inferred water-depth reconstruction. Palaeogeogr Palaeoclimatol Palaeoecol 199:31–49

Anadon P, Cabrera L, Colombo F, Marzo M, Riba O (1986) Syntectonic intraformational unconformities in alluvial fan deposits, eastern Ebro Basin margins (SE Spain). In Allen PA, Homewood P (eds) Foreland basins: International Association of Sedimentologists Special Publication 8, pp 259–271

Anselmetti FS, Ariztegui D, Hodell DA, Hillesheim M, Brenner M, Gilli A, KcKenzie JA, Mueller AD (2006) Late quaternary climate-induced lake level variations in Lake Petén-Itzá, Guatemala, inferred from seismic stratigraphic analysis. Palaeogeogr Palaeoclimatol Palaeoecol 230:52–69

Bergonzini L, Chalie F, Gasse F (1997) Paleoevaporation and paleoprecipitation in the Tanganyika Basin at 18,000 yr BP inferred from hydrologic and vegetation proxies. Quat Res 47:295–305

Bohacs KM, Carroll AR, Neal J, Mankiewicz P (2000) Lake Basin Type, Source Potential, and Hydrocarbon Character: An Integrated Sequence-stratigraphic-geochemical Framework. In Gierlowski-Kordesch E, Kelts K (eds) Lake Basins through Space and Time: AAPG Studies in Geology 46, pp 3–34

Bouroullec JL, Rehault JP, Rolet J, Tiercelin JJ, Mondequer A (1991) Quaternary sedimentary processes and dynamics in the northern part of the Lake Tanganyika trough, East Africa Rift System. Evidence of lacustrine eustatism? Bulletin Centres de Recherche et Exploration. Elf-Aquitaine 15:343–368

Burbank DW, Anderson RS (2001) Tectonic geomorphology: a frontier in earth science. Blackwell Publishing

Capart A (1952) Le milieu géographique et géophysique, Résultats scientifiques de l'exploration hydrobiologique du Lac Tanganika (1946–1947). Institut Royal des Sciences Naturelles de Belgique 1:3–27

Carroll AR, Bohacs KM (1999) Stratigraphic classification of ancient lakes: Balancing tectonic and climatic controls. Geology 27:99–102

Chalié F (1995) Paléoclimats du bassin Tanganyika Sud au cours des 25 derniers mille ans: reconstitution quantitative par le traitement statistique des données polliniques. CR Acad Sci Paris 320:205–210

Cohen AS, Thouin C (1987) Near shore carbonate deposits in Lake Tanganyika. Geology 15:414–418

Cohen AS, Lezzar KE, Russell J, Scholz CA, Tiercelin JJ, Gans C, Helfrich CL (2004) The Lake Tanganyika Accomodation Zone Structural Highs: probable archive of continuous miocene to recent paleoenvironmental and paleoclimatic information for East Africa. AGU Ann Mtg Abstr w/Prog

Cohen AS, Lezzar KE, Tiercelin JJ, Soreghan M (1997) New paleogeographic and lake level reconstructions of Lake Tanganyika: implications for tectonic, climatic and biological evolution in a rift lake. Basin Res 9:107–132

Cohen AS, Soreghan MJ, Scholz CA (1993) Estimating the age formation of lakes: an example from Lake Tanganyika, East African Rift system. Geology 21:511–514

Cohen AS, Stone JR, Beuning KRM, Park LE, Reinthal PN, Dettman D, Scholz CA, Johnson TC, King JW, Talbot MR, Brown ET, Ivory SJ (2007) Ecological Consequences of Early Late-Pleistocene Megadroughts in Tropical Africa. PROC NATL ACAD SCI USA 104: 16422–16427

Coulter GW, Spigel RH (1991) Hydrodynamics. In: Coulter GW (ed) Lake Tanganyika and its Life. Oxford University Press, London, pp 49–75

Craig H, Dixon F, Craig V, Edmond J, Coulter G (1974) Lake Tanganyika geochemical and hydrographic study: 1973 expedition. Scripps Institution of Oceanography, Publication 75:1–83

D'Agostino K, Seltzer GO, Baker PA, Fritz S, Dunbar R (2002) Late-Quaternary Lowstands of Lake Titicaca: evidence from high-resolution seismic data. Palaeogeogr Palaeoclimatol Palaeoecol 179:97–111

Dettman D, Palacios-Fest MR, Nkotagu HH, Cohen AS (2005) Paleolimnological investigations of anthropogenic environmental change in Lake Tanganyika: VII Carbonate isotope geochemistry as a record of riverine runoff. J Paleolimnol 34:93–105

Felton AA, Russell JM, Cohen AS, Baker ME, Chesley J, Lezzar K-E, McGlue MM, Pigati JS, Quade J, Stager JC (2007) Paleolimnological evidence for the onset and termination of glacial aridity from Lake Tanganyika, East Tropical Africa. Palaeogeogr Palaeoclimatol Palaeoecol 252:405–423

Farrera I, Harrison SP, Prentice IC, Ramstein G, Guiot J, Bartlein PJ, Bonnefille R, Bush M, Cramer W, von Grafenstein U, Holmgren K, Hooghiemstra H, Hope G, Jolly D, Lauritzen S-E, Ono Y, Pinot S, Stute M, Yu G (1999) Tropical climates at the Last Glacial Maximum: a new synthesis of terrestrial paleoclimate data I vegetation, lake-levels and geochemistry. Clim Dyn 15:823–856

Gasse F (2000) Hydrological changes in the African tropics since the Last Glacial Maximum. Quat Sci Rev 19: 189–211

Gasse F, Ledee V, Massault M, Fontes J-C (1989) Water-level fluctuations of Lake Tanganyika in phase with oceanic changes during the last glaciation and deglaciation. Nature 342:57–59

Gawthorpe RL, Sharp IR, Underhill JR, Gupta S (1997) Linked sequence stratigraphic and structural evolution of propagating normal faults. Geology 25:795–798

Gilbert GK (1890) Lake Bonneville. U.S. Geol Surv Monogr 1:1–275

Haberyan KA, Hecky RE (1987) The late Pleistocene and Holocene stratigraphy and paleolimnology of Lakes Kivu and Tanganyika. Palaeogeogr Palaeoclimatol Palaeoecol 61:169–197

Hardy S, McClay KR (1999) Kinematic modeling of extensional fault-propagation folding. J Struct Geol 21:695–702

Hastenrath SL, Kutzback JE (1983) Paleoclimatic estimates for water and energy balance budgets of East African Lakes. Quat Res 19:141–153

Hecky RE, Degens ET (1973) Late Pleistocene-Holocene chemical stratigraphy and paleolimnology of the Rift Valley lakes of Central Africa. Technical Report, Woods Hole Oceanographic Institute, pp 1–144

Johnson TC, Brown ET, McManus J, Barry S, Barker P, Gasse F (2002) A high-resolution paleoclimate record spanning the past 25,000 years in Southern East Africa. Science 296:113–115

Johnson TC, Scholz CA, Talbot MR, Kelts K, Ricketts RD, Ngobi G, Buening K, Ssemmanda I, McGill JW (1996) Late Pleistocene desiccation of Lake Victoria and rapid evolution of cichlid fishes. Science 273:1091–1093

Koeberl C, Peck J, King J, Milkereit B, Overpeck J, Scholz CA (2005) The ICDP Lake Bosumtwi drilling project: A first report. Scientific Drilling 1:23–27

Kutzbach JE , Street-Perrott FA (1985) Milankovitch forcing of fuctuations in the level of tropical lakes from 18 to 0 kyr BP. Nature 317:130–134

Lezzar KE, Tiercelin J-J, De Batist M, Cohen AS, Bandora T, Van Rensbergen P, Le Turdu C, Wafula M, Klerkx J (1996) New seismic stratigraphy and Late Tertiary history of the North Tanganyika Basin, East African Rift system, deduced from multifold reflection and high resolution seismic data and piston core evidence. Basin Res 8:1–28

Lezzar KE, Tiercelin J-J, Le Turdu C, Cohen AS, Reynolds DJ, Le Gall B, Scholz CA (2002) Control of normal fault interaction on the distribution of major Neogene sedimentary depocenters, Lake Tanganyika, East African rift. AAPG Bull 86:1027–1059

Livingstone DA 1965 Sedimentation and the history of water level change in lake Tanganyika. Limnol Oceanogr 10: 607–610

McKee BA, Cohen AS, Dettman DL, Palacios-Fest MR, Alin SA, Ntungumburangye G (2005) Paleolimnological investigations of anthropogenic environmental change in Lake Tanganyika: II: Geochronologies and mass sedimentation rates based on 14C and 210Pb data. J Paleolimnol 34:19–29

McGlue MM, Scholz CA, Karp T, Ongodia B, Lezzar K-E (2006) Facies architecture of flexural margin lowstand delta deposits in Lake Edward, East African Rift: Constraints from seismic reflection imaging. J Sed Res 76:942–958

Mitchum RM, Vail PR, Sangree JB (1977) Seismic stratigraphy and global changes of sea level, part 6: stratigraphic interpretation of seismic reflection patterns in depositional sequences, In: Payton CE (ed) Seismic Stratigraphy-applications to hydrocarbon exploration. AAPG Memoir 26, pp 117–133

Mondeguer A (1991) Bassins sédimentaires en contexte extensive et décrochant: l'exemple du "Complexe de fossés Sud-Tanganyika," Rift Est-Africain. Morphostructures et sédimentation. University of Western Brittany, Brest, France

Morley CK (1989) Extension, Detachments and Sedimentation in Continental Rifts (With Particular Reference to East Africa). Tectonics 8:1175–1192

Nicholson SE (1996) A review of climate dynamics and climate variability in eastern Africa. In: Johnson TC, Odada EO (eds) The limnology, climatology, and paleoclimatology of the East African Lakes. Gordon and Breach, Amsterdam, pp 25–56

Nyblade AA, Brazier RA (2002) Precambrian lithospheric controls on the development of the East African rift system. Geology 30:755–758

Placzek C, Quade J, Patchett PJ (2006) Geochronology and stratigraphy of plate Pleistocene lake cycles on the southern Bolivian Altiplano: implications for causes of tropical climate change. Geol Soc Am Bull 118:515–532

Porebski SJ, Steel RJ (2006) Deltas and sea level change. J Sed Res 76:390–403

Riba O (1976) Syntectonic unconformities of the Alto Cardener, Spanish Pyrenees: a genetic interpretation. Sed Geol 15:213–233

Rosendahl BR (1988) Seismic Atlas of Lake Tanganyika, East Africa: Project Probe Geophysical Atlas Series. Duke University, Durham

Schlische RW, Olsen PE (1990) Quantitative filling model for continental extensional basins with application to early Mesozoic rifts of Eastern North America. J Geol 98:135–154

Scholz CA (1995) Deltas of the Lake Malawi Rift, East Africa: Seismic expression and exploration implications. AAPG Bull 79:1679–1697

Scholz CA (2001) Applications of seismic sequence stratigraphy in Lacustrine basins. In: Last WM, Smol JP (eds) Tracking environmental changes in Lake Sediments: physical and chemical techniques. Kluwer Academic Publishers, Dordrecht, The Netherlands

Scholz CA, Rosendahl BR (1988) Low lake stands in Lakes Malawi and Tanganyika, East Africa, delineated with multifold seismic data. Science 240:1645–1648

Scholz CA, Cohen AS, Johnson TC, King JW (2006) The 2005 Lake Malawi Scientific Drilling Project. Scientific Drilling 2:17–19

Scholz CA, Johnson TC, Cohen AS, King JW, Peck J, Overpeck JT, Talbot MR, Brown ET, Kalindekafe L, Amoako PYO, Lyons RP, Shanahan TM, Castenada IS, Heil CW, Forman SL, McHargue LR, Beuning KR, Gomez J, Pierson J (2007) East African megadroughts between 135–75 kyr ago and implications for early human history. PROC NATL ACAD SCI USA 104:16416–16421

Scholz CA, King JW, Ellis GS, Swart PK, Stager C, Colman SM (2003) Paleolimnology of Lake Tanganyika, East Africa, over the past 100 kyr. J Paleolimnol 30:139–150

Soreghan MJ, Scholz CA, Wells JT (1999) Coarse-grained deep-water sedimentation along a border fault margin of Lake Malawi, Africa: seismic stratigraphic analysis. J Sed Res 69:832–846

Street FA, Grove AT (1979) Global maps of lake level fluctuations since 30,000 BP. Quat Res 12:83–118

Sturmbauer C, Meyer A (1992) Genetic divergence, speciation and morphological stasis in a lineage of African cichlid fishes. Nature 358:578–581

Swirydczuk K, Wilkinson BH, Smith GR (1980) The Pliocene Glenn's Ferry Oolite-II: Sedmentology of Oolitic Lacustrine Terrace Deposits. J Sed Petrol 50:1237–1248

Talbot MR, Delibrias G (1980) A new late Pleistocene-Holocene water-level curve for Lake Bosumtwi, Ghana. Earth Planet Sci Lett 47:336–344

Thompson TA (1992) Beach ridge development and lake level variation in southern Lake Michigan. Sed Geol 80:305–318

Tiercelin J-J, Mondeguer A (1991) The geology of the Tanganyika trough. In: Coulter GW (ed) Lake Tanganyika and its life. Oxford University Press, London

Tiercelin J-J, Scholz CA, Mondeguer A, Rosendahl BR, Ravenne C (1989) Discontinuites sismiques et sedimentaires dans la serie de remplissage du fosse du Tanganyika, Rift Est Africain, [Seismic and sedimentary discontinuities in the Lake Tanganyika Rift, East Africa]. CR Acad Sci Paris 309:1599–1606

Tierney J, Russell JM (2007) Abrupt Climate change in Southeast Tropical Africa influenced by Indian monsoon variability and ITCZ migration. Geophys Res Lett 34:1–6

Verheyen E, Salzburger W, Snoeks J, Meyer A (2003) Origin of the Superflock of Cichlid Fishes from Lake Victoria, East Africa. Science 300:325–329

Versfelt J, Rosendahl BR (1989) Relationship Between Pre-Rift Structure and Rift Architecture in Lakes Tanganyika and Malawi, East Africa. Nature 337:3–356

Vincens A, Chalié F, Bonnefille R, Guiot J, Tiercelin J-J (1993) Pollen-Derived Rainfall and Temperature Estimates from Lake Tanganyika and Their Implication for Late Pleistocene Water Levels. Quat Res 40:343–350

Wetzel RG (2001) Limnology: lake and river ecosystems. Academic Press, San Diego

White F (1983) The vegetation of Africa a descriptive memoir to accompany the UNESCO/AETFAT/UNSO vegetation map of Africa. UNESCO, Paris, pp 356

Williamson D, Thouveny N, Hillaire-Marcel C, Mondeguer A, Taieb M, Tiercelin J-J, Vincens A (1991) Chronological potential of palaeomagnetic oscillations recorded in late quaternary sediments from Lake Tanganyika. Quat Sci Rev 10:351–361

Yoo DG, Park SC (2000) High-resolution seismic study as a tool for sequence stratigraphic evidence of high-frequency sea-level changes: latest Pleistocene-Holocene example from the Korea Strait. J Sed Res 70:296–307