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FACIES ARCHITECTURE OF FLEXURAL MARGIN LOWSTAND DELTA DEPOSITS IN LAKE EDWARD, EAST AFRICAN RIFT: CONSTRAINTS FROM SEISMIC REFLECTION IMAGING

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ABSTRACT: **Lake Edward is single half-graben rift basin unique in the East African Rift System as a result of its connection to Lake George via the Kazinga Channel, a paleo–river valley which is incised into the flexural margin of the lake. Using recently acquired normal-incidence seismic reflection data and thirty-three lake-bottom sediment samples, we examine the consequences of this hydrologic connection for understanding depositional processes and facies development along the flexural margin of Lake Edward. Three depositional sequences were defined in the study area based on top and bottom discordances of seismic reflections. Climatically induced changes in lake level appear to have forced sequence development. Sequence I deposits indicate that highstand conditions prevailed earlier in the Pleistocene. Evidence for high-frequency lake-level change comes from lowstand delta clinoforms in two separate stratigraphic intervals on the flexural margin. An older lowstand event occurred during Sequence II time and reduced lake level by at least ~ 37 m. A younger lowstand event occurred during the deposition of Sequence III and reduced lake level by ~ 18 m. Clastic sedimentation on the flexural margin of Lake Edward is strongly modified by inflow from the Kazinga Channel and Lake George during periods of lowered lake level. We suggest that the presence of an incised valley at the margin of the rift controls the stratigraphic development of clinoforms diagnostic of lowstand deltaic sedimentation. The morphology and orientation of these clinoforms suggest that discharge from Lake George during arid periods utilized the Kazinga Channel to transport sediment toward the exposed flexural margin of Lake Edward. Dipping reflections in sigmoid-oblique clinoforms suggest that these flows were capable of transporting sediment loads that included coarse grain sizes. Deposition by this process occurred several times during the late-Quaternary history of Lake Edward, and represents an important modern analogue for linked incised valley–lacustrine delta sequences in the stratigraphic record.**

INTRODUCTION

The sedimentary deposits of the Great Lakes of the East African Rift Valley are strongly influenced by extension of the continental crust. Clastic material deposited in the deeply subsided rift valley basins is commonly derived from uplifted rift-margin drainage basins that have been modified by processes of continental extension. In East Africa, this is especially evident near the northern end of the Western Rift Valley, where surface uplift associated with the formation of the Edward and Albert rift basins has reversed several major drainage systems (Kendall 1969; Beadle 1981; Ollier 1990). The largest of these drainage systems, the Katonga, Kagera, and Kafu rivers, once drained the highlands of southern Kenya and flowed unimpeded across the Tanzania Craton (Fig. 1; Bishop and Trendall 1967; Beadle 1981). Today these rivers are much diminished and flow bidirectionally, originating from wetland drainage divides atop a broad upwarp in western Uganda (Fig. 1). Lakes Victoria and Kyoga were both formed by these drainage reversals and by the topography created by the growth of rift shoulder segments to the west (Bishop 1969). The Great Lakes of the rift valley are renowned for their endemic faunas, and genetic evidence suggests that tectonically induced drainage reversals have played a role in the evolution of cichlid fishes and other endemic species (Meyer et al. 1996; Verheyen et al. 2003).

Today, the westward-flowing remnants of the Katonga (Fig. 1) and Kagera Rivers are components of the watershed of Lake Edward. Lake Edward is composed of a single half-graben rift segment, and is structurally and depositionally a simpler system than either lakes Tanganyika or Malawi to the south. Those large, deep lakes contain multiple depositional basins separated by accommodation zones and transfer faults, with corresponding complex depositional pathways (e.g., Rosendahl 1987). Accordingly, separating the influences of tectonics and sedimentation on rift-system stratigraphic architecture may be an easier task using Lake Edward as a modern analogue for ancient rift-lake systems, rather than either of those larger lake basins. Cutting across the flexural margin of Lake Edward is the deeply incised Kazinga Channel, a 40-km-long valley that extends to the margin of the rift valley. The channel links the flexural margin of Lake Edward to Lake George, a hyper-eutrophic lake system situated near the southeastern flank of the Ruwenzori Mountains. Significantly, some of the largest syn-rift hydrocarbon reservoirs in ancient producing basins are observed on flexural margins of rift basins (Trudgill and Underhill 2002). This paper reports the results of an integrated reflection seismic–sedimentological

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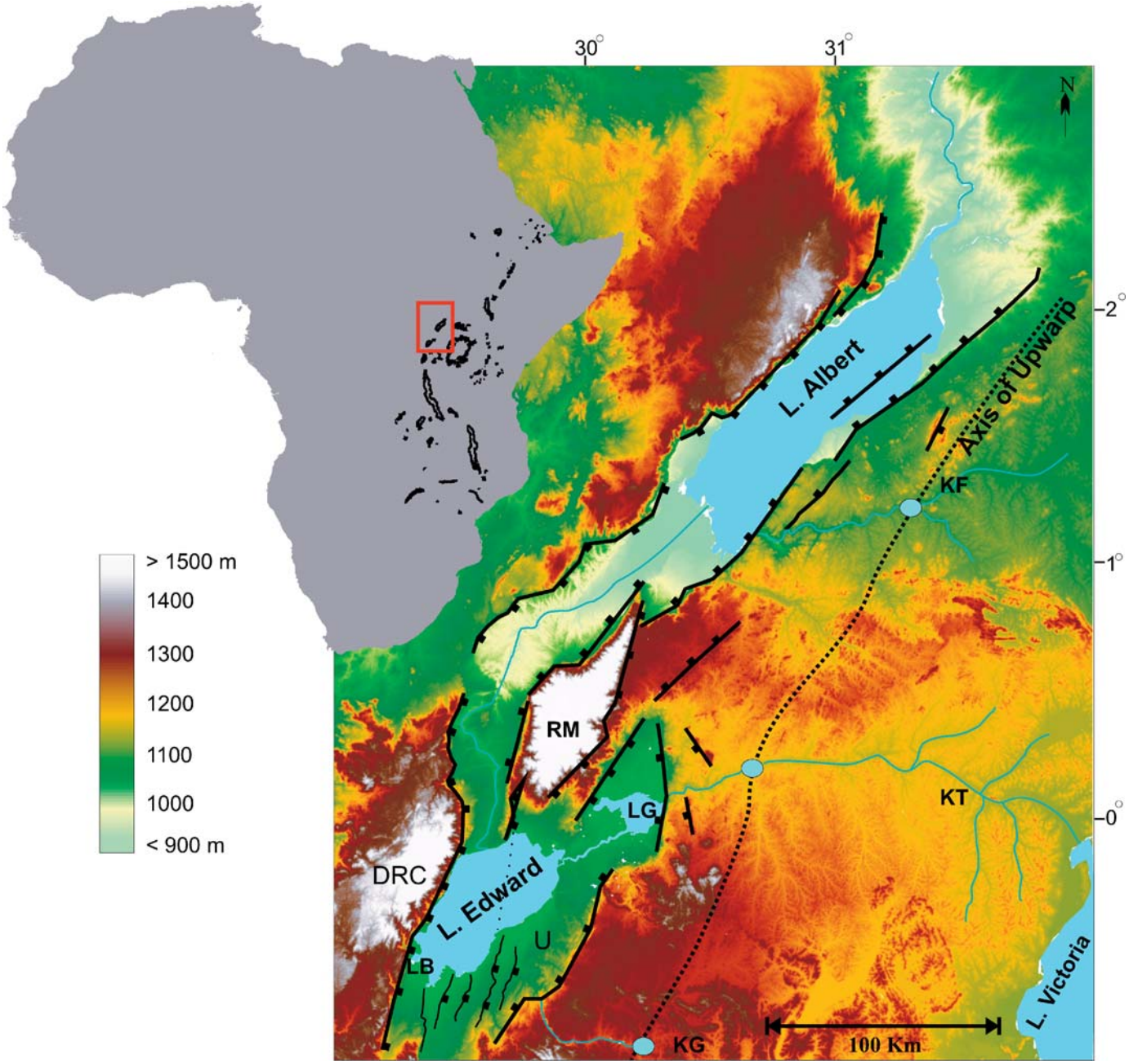


FIG. 1.—Map of the African continent and the East African Rift System. Inset map is a tectonic and digital elevation model (SRTM90) overview in the Lake Edward region. Fault interpretations are modified from Ebinger (1989). Blue circles mark the location of drainage reversals formed from rift-related surface uplift. The dotted line across Lake Edward denotes the international boundary between Uganda (east) and the Democratic Republic of the Congo. DRC = Democratic Republic of the Congo. U = Uganda. RM = Ruwenzori Mountains. LG = Lake George. KF = Kafu River. KT = Katonga River. KG = Kagera River. LB = Lubero Border Fault (after Laerdal and Talbot 2002).

study focused on sedimentation on a flexural margin that is linked to a major rift-basin incised valley.

The goals of this study are to: (1) provide the first seismic stratigraphic framework for Lake Edward, (2) characterize seismic facies observed in the study area; and (3) provide an explanation of the facies distribution in terms of tectonic, climatic, and limnologic processes, especially with respect to the influence of the Kazinga Channel incised-valley system.

BACKGROUND

Regional Geologic Overview

Lake Edward lies immediately south of the equator at the northern end of the Western Rift Branch of Africa's Great Rift Valley, and it straddles the border of Uganda and the Democratic Republic of the Congo (Fig. 1). The Western Branch of the East African Rift System developed

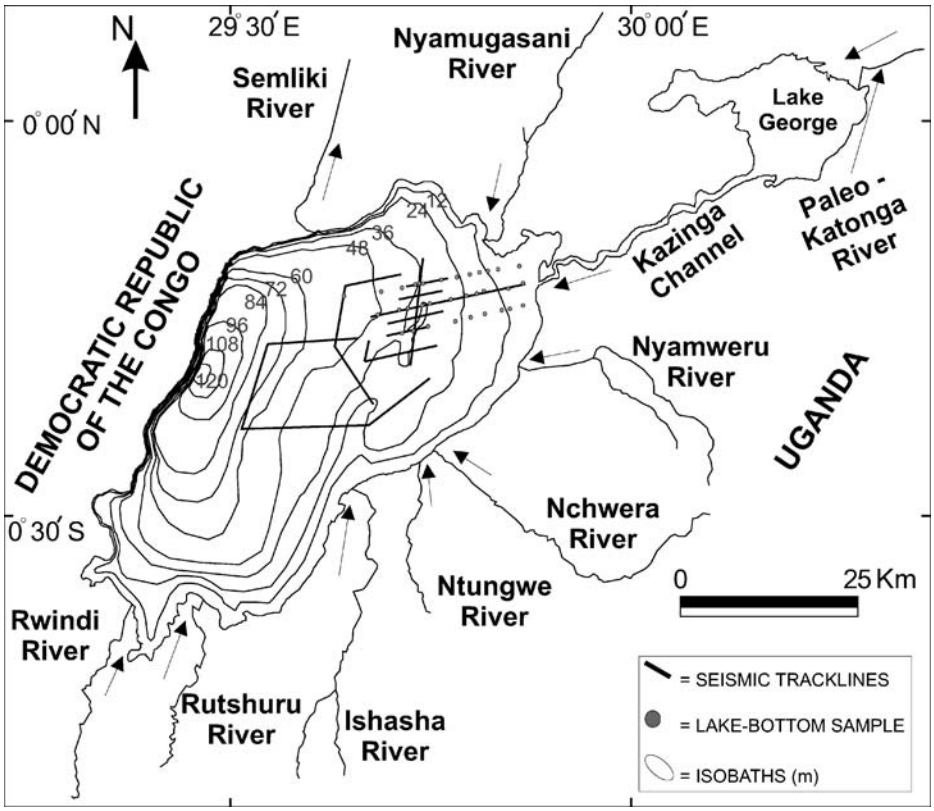


FIG. 2.—Bathymetric, seismic reflection trackline, and sediment grab sample location map of Lake Edward with major rivers. Isobaths are constructed from seismic reflection data and compiled from other sources. The contour interval is 12 m.

beginning in the Miocene along the western edge of the Tanzania Craton (Nyblade and Brazier 2002). The Western Rift Valley is composed of half-graben rift basins that are typically 80–160 km long, 30–80 km wide, and linked end to end along the rift axis (Rosendahl et al. 1986). Rift basins are asymmetric, and are defined structurally by major basin-bounding border faults and an opposing flexural or shoaling margin (Rosendahl 1987).

The Lake Edward rift consists of a single asymmetric half-graben basin. Flexural uplift on the footwall block of the Lubero Border Fault has produced rift shoulder mountains along the western shoreline of the lake that reach ~ 1.5 km above the modern lake surface (Fig. 1). Gravity data indicate that up to 5 km of sediment fill the depocenter of the basin, suggesting that total basement relief approaches 6.5 km in some locations along the Lubero Fault (Upcott et al. 1996). Onshore topography along the flexural eastern margin of the lake is much more subdued, distinguished more by volcanic craters and small normal-fault scarps (Laerdal and Talbot 2002; Upcott et al. 1996). The rift flanks of Lake Edward are composed of late Proterozoic medium- and high-grade metamorphic rocks (Department of Geological Survey and Mines Uganda 1966). Surficial deposits around the rift basin are dominantly Pleistocene-age fluvial and lacustrine sedimentary sequences (Bishop 1969). Two Cenozoic volcanic provinces in the region, Toro Ankole and Virunga, are the source of volcaniclastic deposits found in close proximity to the lake basin (Beadle 1981).

Hydrology and Climate

Lake Edward is ~ 80 km long and up to 40 km wide and has a maximum water depth of ~ 117 m (Fig. 2; Lehman 2002). Major rivers emptying into Lake Edward flow along the axis of the rift basin or transverse to the rift axis, where the low-gradient landscape has allowed large drainage systems to develop (Frostick and Reid 1989; Cohen 1990). Among the largest river inputs in the watershed of the lake are the Rutshuru and Rwindi rivers, which drain the Virunga Volcanoes to the south (Fig. 2). Rivers such as the Nyamugasani River, which drains the Ruwenzori Mountains to the north, also discharge into the lake. A unique feature of the watershed of Lake Edward is its connection to Lake George, a shallow basin attached to Lake Edward through the Kazinga Channel (Fig. 2). Flow through the Kazinga Channel is barely measurable, because the two lakes are at nearly the same elevation, although net transport is toward Lake Edward (Beadle 1981). The broad, shallow channel is an incised valley whose meandering course may be a consequence of extension-related faulting and surface uplift (Laerdal and Talbot 2002). Lake Edward is an open hydrologic system, draining to the north into Lake Albert through the Semliki River, although most water is lost through direct evaporation (Lehman 2002). Lake Edward is also an important reservoir for tropical precipitation in the Upper Nile Watershed (UNW), the equatorial headwaters of the main Nile River.

The modern climate of the region is governed by the convergence of two air masses: the Congo Air Stream and Indian Ocean monsoons (Nicholson 1996). Annual rainfall in the region averages 0.9 m/yr, during two rainy seasons from October to December and March to May, which occur as a result of the migration of the Intertropical Convergence Zone (Nicholson 1996; Viner and Smith 1973). The average annual temperature near Lake Edward is ~ 25°C. Due to its position on the equator and the influence of multiple moisture sources, the sedimentary archives of Lake Edward have been studied for reconstructing recent, high-resolution changes in climate (e.g., Russell et al. 2003a; Russell et al. 2003b), and the basin holds promise for longer records of tropical climate change. The lake is oligomictic, experiencing sporadic mixing following particularly intense wind and rainstorms (Hecky and Degens 1973). Lake waters are permanently anoxic below 80 m, although the position of the oxycline varies and anoxic bottom waters have been measured at depths as low as 30 m (Beadle 1981; Hecky and Degens 1973).

METHODS

Approximately 200 km of high-resolution single-channel digital seismic reflection data were collected from the northern half of Lake Edward in 2003 (Fig. 2). In some areas these data overlap with a limited-extent seismic reflection survey conducted in 1999 (Laerdal and Talbot 2002). The survey followed a grid pattern with ~ 1.5 km line spacing, that permits detailed seismic stratigraphic, acoustic facies, and structural component mapping along the flexural margin. Navigation data were acquired during the survey using a Trimble AG132 real-time differential GPS system for sub-meter positioning. The seismic signals were generated using a Geoacoustics Geopulse boomer system operating at 280 J with a 1000 ms shot interval. The dominant data frequency is ~ 1 kHz, producing a vertical resolution of < 0.5 m. An ORE 20-element towed-hydrophone array acted as the signal receiver, which was interfaced with a Triton-Elics Delph 2.5 seismic acquisition system. The sample rate is 0.125 ms, and data were collected with a record length of 2000 ms. Data presented in this study were processed using Promax 2D software, and a bandpass filter (200–2000 Hz), top-mute, and a 15 ms AGC window were applied. The seismic profiles were depth-converted assuming a constant P-wave velocity of 1450 m/s.

Thirty-three lake-bottom grab samples were collected using an oceanographic dredge during the same survey (Fig. 2). The sampling strategy focused on retrieval of lake bottom sediment for every 5 m change in water depth. Samples were collected along three seismic reflection track lines to "ground truth" the acoustic character of uppermost reflections and to infer offshore sedimentary processes and depositional environments. Samples were analyzed for texture and composition using standard wet sieve/pipette, X-ray diffraction, and smear-slide techniques. Abundances of organic C and N were determined using a Costech Elemental Analyzer, following standard pretreatment procedures.

RESULTS

Intrabasinal Fault Structure from Seismic Reflection Data

Two active secondary normal faults displace the water-bottom reflection and form bathymetric highs along the flexural margin of Lake Edward. The northernmost bathymetric high is located ~ 18 km from the mouth of the Kazinga Channel. This feature was recognized in the past on remote-sensing images and seismic profiles and mapped as a > 20 km long, north–south striking normal fault that possibly extends onshore, controlling the channel position of the Ishasha River (de Heinzelin and Verniers 1996; Laerdal and Talbot 2002). New data from this study indicate that the length of this fault segment is actually ~ 10 km, considerably shorter than previously interpreted (Fig. 3). This fault segment, named the Kasindi Fault (after the terminology of Laerdal and Talbot 2002) is an eastward-dipping normal fault, synthetic to the basin-bounding border fault (Fig. 4). The Kasindi Fault strikes NE–SW, suggesting the dominant direction of extensional stress in the basin is approximately NW–SE. Near the center of the Kasindi Fault, the lake floor is displaced approximately 10.5 m (Fig. 4).

The new data acquired in 2003 clearly indicate that another escarpment 12 km from the eastern shore is a second active normal fault within the basin, near the border of Uganda and the Democratic Republic of the Congo (Fig. 3). This fault, herein named the Bantu Fault, also strikes NE–SW and produces lake-floor offset of ~ 13 m, down to the southeast (Fig. 4). The Bantu Fault segment is at least 15 km long, although northeast-striking lineaments observed onshore may link with this feature in the southern region of the lake. Whereas the Bantu and Kasindi faults are parallel to one another, their tips do not appear to interact or overlap. In spite of the lake-bottom relief created by the Kasindi and Bantu faults, the flexural margin of Lake Edward has a relatively shallow gradient: from the eastern shore toward the Bantu Fault near the international border, the slope of the lake floor is ~ 1°.

Numerous other minor normal faults are present in the study area, especially adjacent to the Kasindi and Bantu faults (Fig. 3). The length of these fault segments is typically < 8 km, and they are oriented parallel to subparallel to the Kasindi and Bantu faults. Small-scale faults mapped in the study area are both synthetic and antithetic to the main basin border fault. They are predominantly down-to-the-southeast, northeast-striking faults spaced ~ 3–5 km apart (Fig. 3). Subbottom displacements across these faults are greatest west of the Bantu Fault, although values are generally less than 5 m (Fig. 4). Whereas these minor faults are responsible for small-scale deformation of the sub-bottom sedimentary section, the flexural margin does not appear to have any active fault-controlled channel systems, such as is observed in other East African Rift Valley lakes (e.g., Scholz 1995). Consequently, sediment bypass of allochthonous clastic sediment to deep-water depocenters via downslope channels and canyons, common in lakes Malawi and Tanganyika (Tiercelin et al. 1992; Soreghan et al. 1999) is not a major process in Lake Edward. Deep-water sediments are interpreted to be of predominantly hemipelagic origin.

Seismic Stratigraphy

Three seismic sequences were identified in the shallow subsurface of the study area based on the identification of unconformities, defined by reflection terminations. This group of sequences is referred to as the Konjo Sequence Set. These sequences are labeled I to III from oldest to youngest, respectively. The maximum sediment thickness imaged in the study area is ~ 45 m. The relatively limited penetration attained during this seismic reflection survey is likely due to high production of biogenic gas at or near the sediment–water interface, especially in areas where muddy sediments predominate (e.g., Schubel and Schiemer 1973).

Sequence I is the oldest stratigraphic package interpreted in the study area. Placement of the upper Sequence I boundary was based on an apparent downlap and truncation surface on seismic lines adjacent to the Kasindi Fault (Fig. 5). Proximal to the Kasindi Fault, tilted reflections with apparent dips of ~ 2° progressively terminate from east to west onto a flat underlying reflection (Fig. 5). The downlap surface occurs at a maximum of 49 m below the modern lake surface. West of this locale, Sequence I becomes conformable with Sequence II, except on lines directly adjacent to the Bantu Fault. Tilted reflections terminate onto a high-amplitude, continuous overlying reflection ~ 9 m below lake bottom in this locality (Fig. 6). The base of Sequence I was not interpreted because the deepest intervals of the seismic section within the study area are obscured by the first water-bottom multiple. Consequently, the maximum thickness of this sequence is unknown, although it appears to be the most volumetrically significant sequence of the Konjo Sequence Set.

Sequence II is bounded at its top by a toplap unconformity (Fig. 5). This sequence is divided into two subsequences based on strong internal terminations observed in the seismic section adjacent to the Kasindi Fault. The external geometry of these reflections defines two distinct clinoform patterns. Reflections in Subsequence IIA (lower stratal position) prograde from east to west and terminate against an upper bounding surface by toplap, suggesting an oblique clinoform (Fig. 5). Subsequence IIA clinoforms are found ~ 41 m below modern lake level. Subsequence IIB unconformably overlies Subsequence IIA and exhibits a complex sigmoid oblique clinoform reflection configuration (Fig. 7). Horizontal topset reflections alternate with toplap terminations on seismic lines adjacent to the Kasindi Fault. Within Subsequence IIB, dipping internal reflections prograde towards the west, with a topset–to–foreset transition occurring ~ 37 m below the modern lake surface (Fig. 5). No evidence of well-developed clinoforms was observed west of

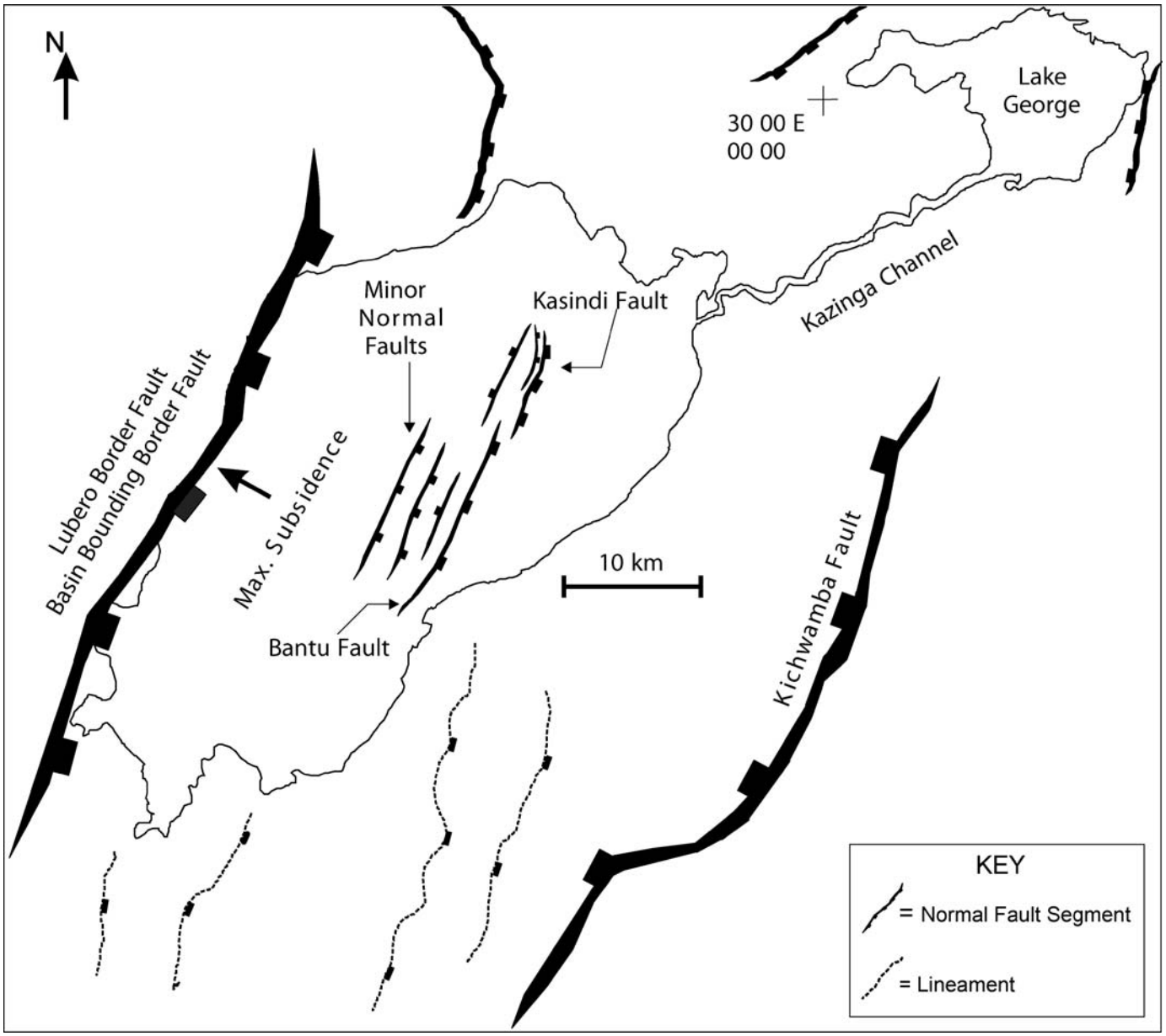


FIG. 3.—Fault map for the Lake Edward rift basin. Intrabasinal faults were mapped using seismic reflection data from this study. Onshore first-order (basin bounding) faults were compiled from Ebinger (1989) and Laerdal et al. (2002) and lineaments were mapped using SRTM90 data. The dominant second-order faults on the flexural margin are the Kasindi and Bantu faults; each display more than 10 m of lake-floor displacement.

the Bantu Fault, where deposition of Sequence II is recorded by the onlap of tilted reflections onto the Sequence I boundary (Fig. 6).

Sequence III is the youngest depositional package in the study area. Placement of the sequence boundary relied on onlapping reflections proximal to the toe of Sequence II clinoforms (Fig. 5). Reflections onlap Subsequence IIB reflections from the west, terminating on the inclined surface formed by dipping strata. The basal onlap occurs ~ 42 m below the modern lake surface (Fig. 5). Over most of the study area, Sequence III conformably overlies Sequence II. Within Sequence III, reflections are continuous and assume the bathymetric relief of the features they blanket. One exception is a small feature imaged ~ 8 km from the mouth of the Kazinga Channel, where reflections are observed to dip slightly, over a distance of ~ 4 km (Fig. 8). The external form and dipping foreslope of this feature is consistent with that of a progradational clinoform package; however, its internal characteristics are not acoustically resolved in this single profile (Fig. 8). The thickness of Sequence III varies over the study area, reaching a maximum of ~ 7 m on the flexural margin and thinning over the footwall blocks of active faults.

Seismic Facies

Four seismic facies were identified in the study area based on the internal character and external form of reflections within the seismic sequences (Table 1). Seismic characteristics such as amplitude, reflection continuity, geometry, and frequency allow us to infer depositional processes operating in the study area (after Damuth 1980). Interpretations of facies types in the uppermost depositional interval are correlated with the sedimentologic character of lake bottom samples collected in the

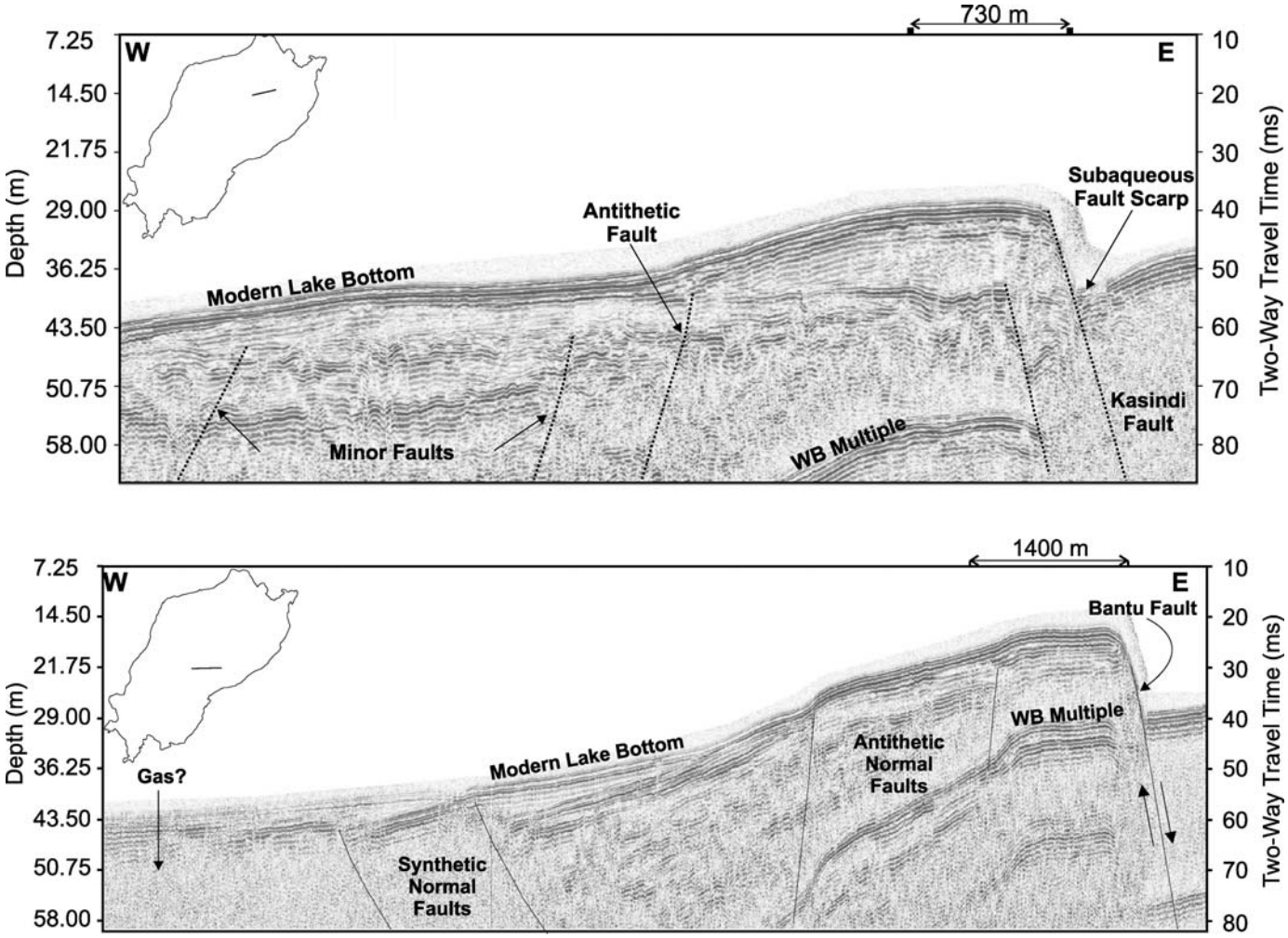


FIG. 4.—Seismic reflection lines illustrating the second-order normal faults in the study area. Inset maps illustrate the positions of the seismic lines in the study area. The vertical axes display both two-way travel time (right) and depth (left). The upper panel displays the Kasindi Fault, the northernmost second-order fault in the study area. The lower panel displays the Bantu Fault, which is located south of the Kasindi Fault and forms a sharp sublacustrine escarpment on the flexural margin.

study area (Fig. 2). Sediment-core lithostratigraphy developed in previous studies on Lake Edward was used to help calibrate acoustic facies at deeper intervals (Laerdal et al. 2002; Russell et al. 2003a).

Sheet-Drape Facies.—This facies consists of high-amplitude, low- to moderate-frequency reflections found at the modern lake bottom (Fig. 9). Reflections in sheet-drape facies are highly continuous and parallel, and this facies exhibits a sheet-like external geometry. The basal surface in this facies type follows the underlying topography, and consequently reflections are wavy or tilted in areas affected by normal faulting. Sheet-drape facies is common in Sequence III, the youngest depositional unit in the study area. The average thickness of sheet-drape deposits in the study area is $\sim$ 3 m (Fig. 7) but this facies type thins dramatically over the Bantu Fault escarpment (Fig. 4). Lake-bottom grab samples indicate that the sheet-drape facies typically consists of organic-rich mud, with lenses of silt common. Total-organic-carbon values for sheet-drape sediments are some of the highest recorded anywhere in the Western Rift Valley, approaching 14% in water depths between 20 and 50 m (Fig. 10).

Basin-Fill Facies.—The basin-fill facies is not expressed at the modern lake-floor surface, but it is volumetrically a significant component of Sequence I. Basin-fill facies consists of moderate- to low-amplitude, moderate-frequency reflections (Fig. 9). Reflections in this facies are organized as semicontinuous to discontinuous events and are sporadically interrupted laterally by divergent, chaotic reflections. The external form of the basin-fill facies is typically wedge shaped. The basal surface of this facies cannot be resolved from the dataset because of a strong water-bottom multiple obscuring the lower section of Sequence I. However, analogues from Lake Malawi suggest that the contact likely contains onlap and internal terminations (Soreghan et al. 1999). The amalgamated acoustic response characterizing basin-fill facies suggests a mixed sediment composition. Sediment cores $>$ 7 m long collected in previous studies west of the Kasindi Fault may have penetrated to stratigraphic intervals marked by basin-fill facies (Russell et al. 2003a). Lithologies present at the deepest intervals of these long cores include massive organic clays or diatom ooze intermixed with sapropel. Basin-fill facies identified in Lake Malawi contains both massive clays intercalated with silt and sand beds (Wells et al. 1999; Soreghan et al. 1999). Consequently, we interpret basin-fill in Lake Edward to be dominantly mud-rich, potentially with interbedded coarser detrital horizons.

Progradational Delta Facies.—This facies consists of low-amplitude, discontinuous reflections arranged in packages of oblique or sigmoid clinoform reflections (Figs. 5, 9). The basal surface underlying the

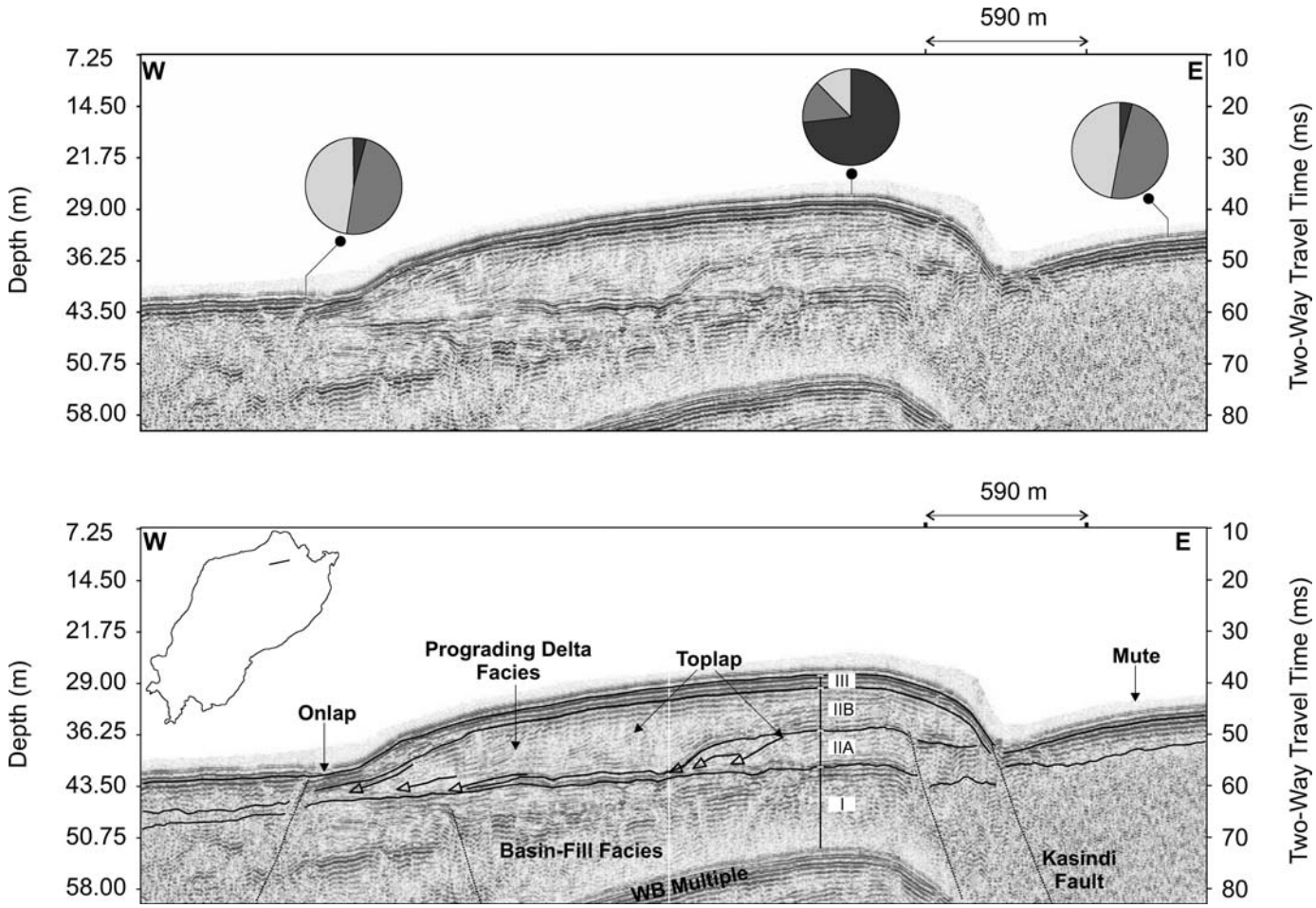


FIG. 5.—Seismic reflection line illustrating the depositional sequences interpreted in this study. The upper panel is an uninterpreted section and contains flags and pie charts marking the location of sediment grab samples. The grayscale of the pie chart illustrates a (sand + gravel)/silt/clay ratio, with coarser fraction represented by darker color. The lower panel is the same seismic reflection line with sequence stratigraphic interpretations (arrows indicate downlapping reflections). The vertical axes display both two-way travel time (right) and depth (left). Note the lobe-shaped Sequence II complex, which is divided into two subsequences. The onlapping reflection at the toe of this lobe was used to identify the Sequence III boundary.

prograding delta facies is planar and is marked by downlap of dipping internal reflections stepping from east to west. The upper bounding surface is convex down and marked by a toplap termination of internal reflections. In sigmoid oblique clinoforms, deltaic foresets alternate with topset reflections suggesting a component of aggradation during deposition. Prograding-delta facies reach a maximum thickness of ~ 18 m and are found primarily in Sequence II, although a smaller, clinoform package is present in Sequence III (Fig. 11). In both cases, prograding delta lobes are bounded laterally by normal faults, which contribute to the bathymetric relief on these deposits. Similar facies in other rift lakes have been interpreted as coarse grained, shallow-water delta deposits (Scholz 1995; Colman et al. 2003). Surface sediment samples recovered over the clinoform reflections are comprised of gravel-size relict gastropod and bivalve shells, shell hash, and minor clastic components. These shells reveal an oolitic fabric in many instances, and exhibit at least two distinct black layers of $(CaMn)CO_3$ coating the fibrous primary carbonate (Fig. 11).

Slope-Front-Fill Facies.—The distribution of slope-front-fill facies in the study area is limited to areas adjacent to the footwall block of the Bantu Fault. This facies consists of low-amplitude, high-frequency reflections onlapping a subaqueous inclined surface (Fig. 6). Significant areas of slope-front-fill are reflection-free, and the external form of this facies type is wedge-shaped. These wedges are typically thin, reaching a maximum of ~ 3.5 m. The acoustic characteristics of this facies type are consistent with homogeneous, bedded sediments (Damuth 1980). A 5 m sediment core collected ~ 8 km west of the Bantu Fault may have penetrated far enough into the subsurface to sample this facies type (Laerdal et al. 2002; Russell et al. 2003a). Lithologies present at the base of this core include tilted beds of organic-rich diatom ooze and massive beds of organic-rich diatomaceous clays (Russell et al. 2003a).

DISCUSSION

Stratigraphic Development

Continental rift systems, especially those with large lakes at tropical latitudes, experience high-frequency climatic perturbations and rapid rates of tectonic subsidence that force the creation of accommodation space and genetically related, unconformity-bounded depositional packages (Scholz and Rosendahl 1988; Schlische and Olsen 1990). In marine settings, sequence development and facies stacking geometries are controlled by eustatic sea-level change, changes in sediment supply mechanisms, and local subsidence variability (Posamentier and Vail 1988). With these variations in scale kept in perspective, we used the basic

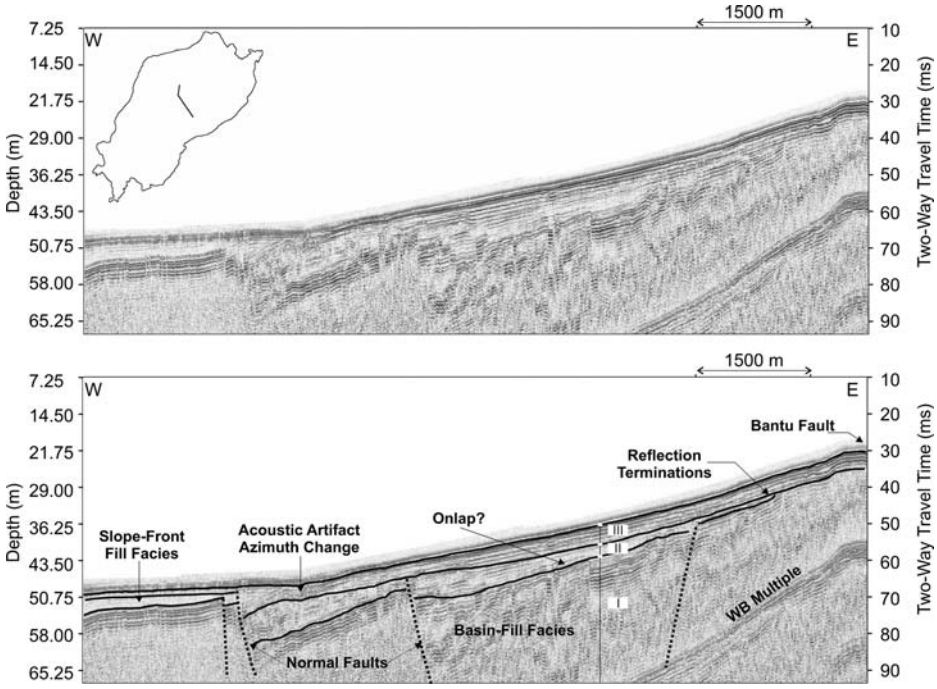


FIG. 6.—Seismic reflection line illustrating the depositional sequences interpreted in this study, west of the Bantu Fault. The upper panel is an uninterpreted section with an inset map to illustrate the position of the seismic line in the study area. The lower panel is the same seismic reflection line with sequence stratigraphic interpretations. The vertical axes display both two-way travel time (right) and depth (left). Note the absence of clinoforms in this locale and the evidence of onlap in Sequence II, which may result from tectonic tilting. This locale in the study area is also marked by the presence of slope-front fill, a facies formed by structural tilting of basement blocks.

principles of sequence stratigraphy to identify chronostratigraphically significant reflections within the seismic data set in the study area. Based upon the vertical resolution of the seismic dataset (< 0.5 m) and the geometry of reflection terminations, high-frequency, climate-driven lake-level changes appear to control the development of the Konjo Sequence Set.

The mode of sedimentation operative during Sequence I time is difficult to resolve precisely due to limited acoustic penetration over the study area. Syn-rift subsidence and structural deformation are interpreted to be the primary mechanisms forming nonhorizontal reflections common throughout this sequence. The downlapping geometry used to place the upper boundary of Sequence I near the Kasindi Fault is associated with prograding units in Sequence II (Fig. 5). We interpret the downlapping reflections to imply lake margin conditions in this area at the Sequence I–II boundary. The topset–foreset transition of the prograding packages, which probably form part of a lowstand delta system, or alternatively, a prograding carbonate system, define the lake shoreline at that time. Cores analyzed by Russell et al. (2003a) indicate that Holocene sedimentation rates at the flexural margin sites are on the order of 1 mm/yr or less. Using this value, and extrapolating to the Sequence I–II boundary (e.g., Figs. 4–6), we interpret an approximate age for the IIA and IIB progradational facies of ~ 18 kyr, or roughly equivalent to the Last Glacial Maximum. In the absence of long cores this age is only an educated guess, but it provides a rough estimate for the timing of a major hydraulic drawdown in the history of the basin. In areas where Sequence I and overlying strata are conformable, we interpret a depositional environment marked by undisturbed hemipelagic sedimentation.

Sequence II contains striking evidence for reduced water levels in Lake Edward. Using the topset-to-foreset transition of sigmoid-oblique clinoforms in Subsequence II B as a proxy for a paleoshoreline (Burbank and Anderson 2000), we interpret a lake-level lowstand of at least 37 m below modern lake level (Fig. 5). This lowstand shifted the shoreline basinward by 16 km, and reduced water volume in Lake Edward by ~ 65%, leading to exposure of most of the flexural margin north and east of the Bantu Fault (Fig. 3). Acoustic variability within Subsequences IIA and IIB reflects sediment supply and water-level dynamics during the time of deposition. Oblique clinoforms observed in Subsequence IIA suggest a short period of low, stable lake level marked by westward-prograding reflections (Fig. 5). Toplap reflection geometries bounding this subsequence suggest sediment bypass and minor erosion and are interpreted as lobe switching in a delta complex. Subsequence IIB is interpreted to have formed as water levels began to rise in the basin. Evidence of rising water levels is manifested in both aggrading and prograding geometries in Subsequence IIB clinoforms. Locations where Sequence II is conformable with Sequence III are interpreted to have remained submerged during this lowstand. We interpret the relief on Sequence II prograding-delta facies to reflect footwall uplift of the Kasindi Fault. The Kasindi normal fault clearly controls the along-strike extent of this facies package on its eastern margin (Fig. 4). However both the Kasindi and the Bantu faults lack growth strata and sedimentary drape, suggesting relatively recent displacement. As a result, we suggest that major movements on these faults occurred following the subsequent rise in lake level at the end of Sequence II time and possibly continued into early Sequence III time. Several authors describe a tectonic lowering of the Semliki River sill during the early Holocene that effectively terminated prevailing highstand conditions (Laerdal et al 2002; Russell et al 2003a). Rising water level at the end of Sequence II time is supported by data from this study and from analysis of pollen records in sediment cores (Beuning and Russell 2004). Consequently, our fault interpretation suggests that the lowering of the Semliki sill height and the formation of the Bantu and Kasindi faults likely occurred simultaneously during a period of heightened tectonism in the basin.

Sequence III onlap geometries suggest rising water levels and the onset of highstand conditions in Lake Edward (Fig. 5). The basal onlap terminates on the toe of Subsequence IIB clinoforms ~ 42 m below the modern lake surface and ~ 1.5 m below modern lake bottom. Reflection amplitude, frequency, and continuity observed within this depositional unit suggest uniform bedding and a stable rain of hemipelagic sediment (Fig. 5). These seismic characteristics are interpreted to reflect a short-lived period of relative climatic and tectonic quiescence. Maximum sediment thickness in Sequence III (~ 7 m) corresponds to the package of prograding reflections near the mouth of the Kazinga Channel (Fig. 8). This clinoform package suggests that the basin has experienced a regression in the recent past, reaching a maximum of 18 m below modern

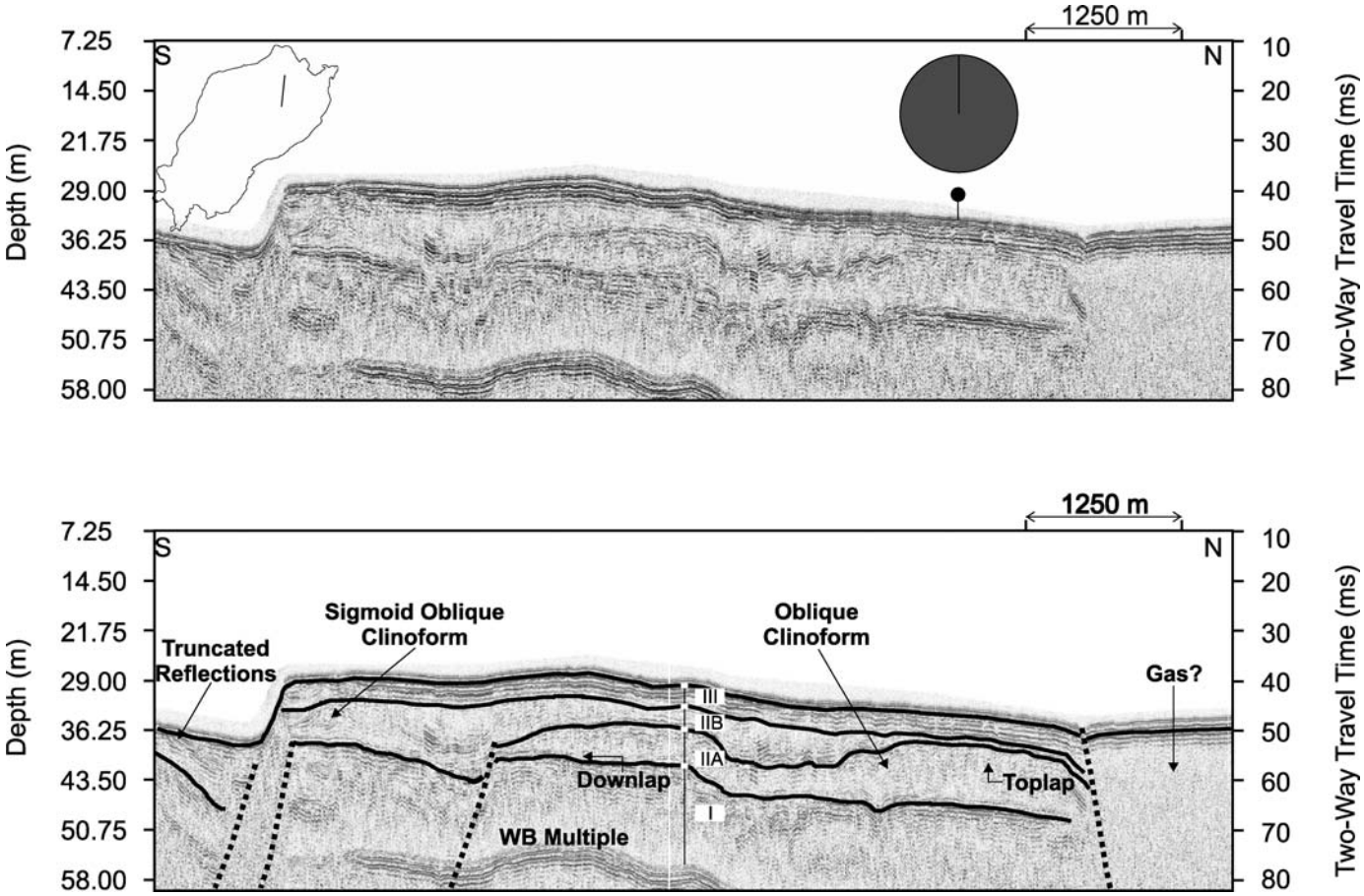


FIG. 7.—Seismic reflection line illustrating the depositional sequences interpreted in this study. The upper panel is an uninterpreted section and contains flags and pie charts marking the location of sediment grab samples. The grayscale of the pie chart illustrates the (sand + gravel)/silt/clay ratio, with coarser fraction represented by darker color. The lower panel is the same seismic reflection line with sequence stratigraphic interpretations. The vertical axes display both two-way travel time (right) and depth (left). This seismic line was collected orthogonal to the line in Figure 6, and is oriented along strike of the Sequence II clinoforms. Oblique clinoforms observed on this line were used to divide Sequence II into two subsequences (see text for details). The "smeared" acoustic response present adjacent to the clinoforms may be a result of interstitial biogenic gas.

lake level. This resulted in a 4 km basinward migration of the shoreline and a reduction of water volume by ~ 45%. Core data are not directly available from this site, but deposition of this package of reflections may be coeval with a well-dated Holocene lowstand established for the basin (Russell et al. 2003a). As water level rose following this lowstand, the depositional mode in the basin returned to highstand conditions.

Controls on Facies Distribution

Sedimentation patterns on the flexural margin of Lake Edward appear to be controlled by interactions between tectonics, fluctuations in base level, and lake-margin physiography. In Lake Edward, we recognize two dominant scales of structural deformation that influence facies distribution and development: (1) rift-scale extension across the border fault, which controls gross drainage basin geomorphology, and (2) localized intrabasinal normal faulting, which influences the present orientation of several important facies types. The lowest depositional sequence in the study area is marked by basin-fill facies (Fig. 9). Basin fill exhibits significant internal acoustic variability due to the proximity of synthetic and antithetic intrabasinal normal faults. Displacement on intrabasinal faults helps to form the nonparallel and chaotic seismic reflections observed in basin fill. Additionally, subsidence on these faults controls the external form of basin-fill facies, forcing expansion and the development of a wedge-shape deposit. Similar facies have been documented in rift lakes along deep-water, border-fault environments, where they were controlled by variable rates of subsidence (Soreghan et al. 1999).

Uplift of the Bantu footwall forms a sharp submerged escarpment along the western margin of the study area and provides the necessary gradient for the development of the onlapping high-frequency internal reflections that characterize slope-front-fill facies (Fig. 6). The base of interpreted slope-front-fill occurs ~ 6 m below lake bottom and ~ 43 m below modern lake level. Based on the wedge-shape external form and internal acoustic properties, we favor tectonics over climate change as the principal control on slope-front facies development. Internal terminations in association with reflection-free areas that result from sedimentary processes such as mass-wasting events or gravity flows instead of climate-related causes have been documented previously in other lacustrine environments (Mullins and Halfman 2001).

Climatically driven variations in the precipitation–evaporation balance affecting the relative position of the lake shore have been documented in seismic reflection data for many large lakes in the East African Rift (Scholz and Rosendahl 1988; Scholz 1995; Johnson et al. 1996; De Batist et al. 1996; Lezzar et al. 1996; Cohen et al. 1997). Scholz (1995) concluded that well-developed deltaic clinoform packages record evidence for large-

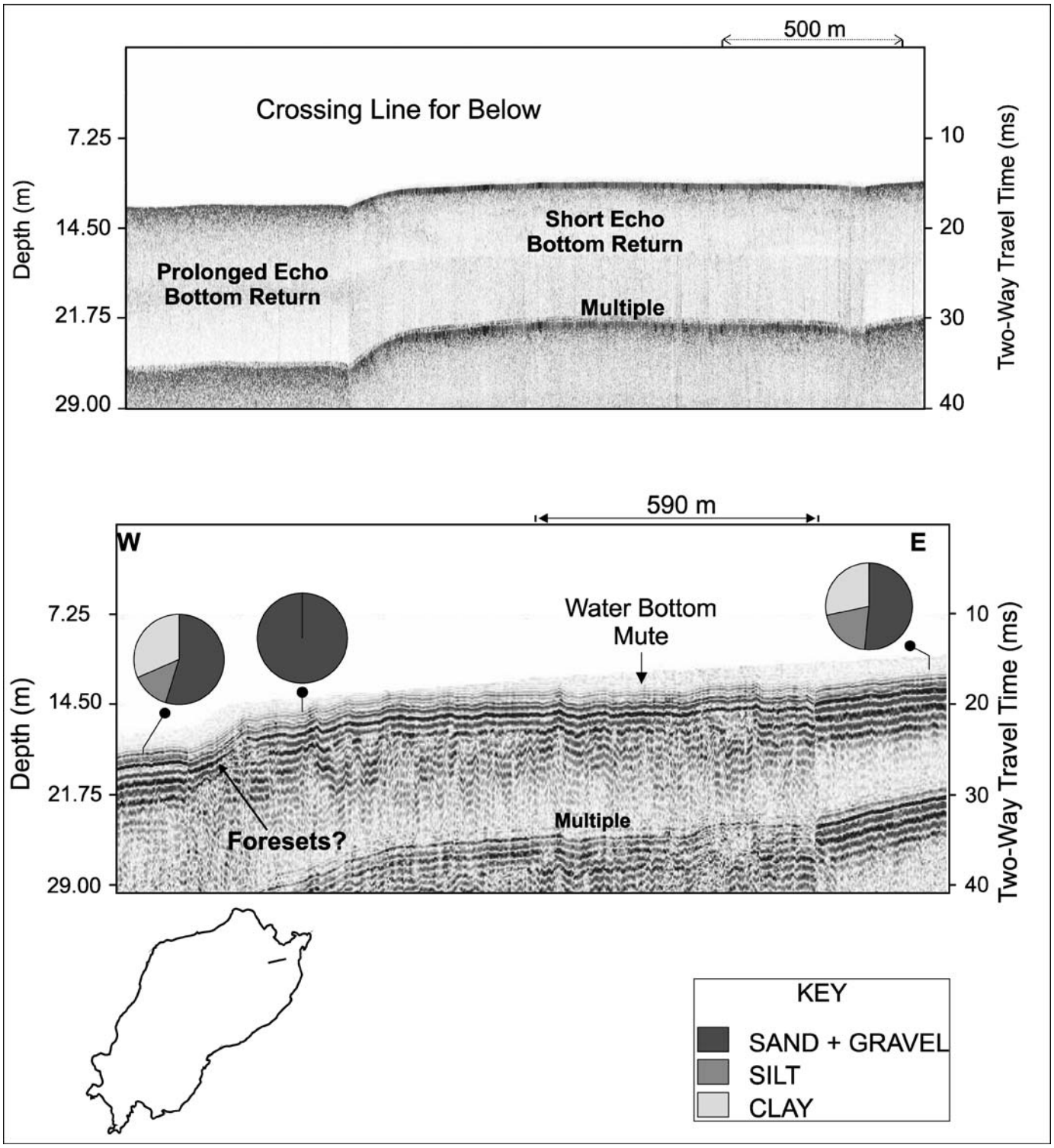
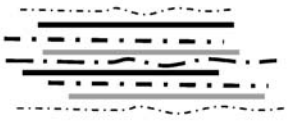
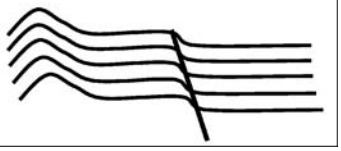


FIG. 8.—Seismic reflection line illustrating the small clinoform package interpreted in Sequence III, reflecting a short-lived lowstand in the recent history of the basin. The upper panel is an uninterpreted 4–24 kHz CHIRP profile along strike of the feature. The vertical axes display both two-way travel time (right) and depth (left). The short-echo, sharp sub-bottom return suggests a coarse substrate, confirmed by sediment grab samples which retrieved shells and shell hash from atop the feature. The bottom panel is a dip-oriented 1 kHz boomer seismic reflection profile which illustrates the dipping foreset reflections used in the interpretation. The feature is located ~ 8 km from the mouth of the Kazinga Channel.

TABLE 1.— *Seismic facies chart for Lake Edward, East African Rift. Total-organic-carbon values are from grab samples (this study) and from sediment core interpretations in Laerdal et al. (2002) and Russell et al. (2003a).*

FACIES TYPE	EXTERNAL GEOMETRY	INTERNAL CHARACTER	PROBABLE LITHOLOGY	TOC	ILLUSTRATION
Basin Fill	Sheet or lens shaped; shape locally influenced by faults	Moderate- to high-amplitude, continuous reflections; often intermixed with low-amplitude reflections that are disrupted or chaotic	Massive organic mud interbedded with coarser clastics	8–12%	
Slope-Front Fill	Wedge shaped; inclined	Low-amplitude continuous reflections onlapping slope front; locally reflection free	Organic-rich diatom ooze and diatomaceous clay	< 8%	
Prograding Delta	Bank or lobe shaped prograding clinoform; oblique or complex sigmoid oblique	Moderate- to low-amplitude reflections, dipping foreset beds a) terminating in toplap unconformity or b) aggrading and lateral outbuilding by foreset-to-topset transition	Delta-front coarse clastics?	Carbonate (Bioclastic Gravel)	
Sheet Drape	Sheet drape, mounded locally	High-amplitude, continuous and parallel; locally disrupted by faults	Organic-rich calcareous mud with lenses of silt	5–14%	

magnitude lake-level fluctuations in Lake Malawi. Similar features are clearly observed in the Lake Edward seismic dataset and attest to climatically driven lake-level change during Sequence II and Sequence III time. Following the Lake Malawi analog, we would expect to observe feeder channel systems forming a pathway from the modern delta mouth to the imaged lowstand delta sediments. These channels are not observed, perhaps in part due to limited acoustic penetration, but we speculate that they emanate from the Kazinga Channel, which is the system best oriented to deliver sediment to the prograding clinoforms interpreted in the study area (e.g., Fig. 11). The limited seismic penetration in this data set is largely due to an extensive gas curtain evident in the fine-grained parts of the sedimentary section. Because Lake Edward is a eutrophic system and because TOC values in the basin are among highest observed in the Great Lakes of Africa, methane production in the upper part of the sediment column is highly effective in limiting the penetration of seismic signals in many areas. The lack of observed feeder channels is probably due to this selective imaging, and we speculate that a more energetic seismic source is required to acoustically penetrate through the upper gaseous material and determine the presence or absence of feeder channels to the clinoform deposits.

Prograding Sequence II delta facies observed in Lake Edward are fan-shaped in plan view and exhibit pronounced east–west dipping reflections, indicating east-to-west sediment pathways (Fig. 11). Accordingly it is unlikely that large rivers entering the flexural margin of the basin obliquely, such as the Ishasha or Ntungwe rivers, acted as a source for the prograding delta lobes. Smaller rivers entering the lake orthogonally, such as the Nchwera and Nyamweru rivers, have quite small drainage basins that appear insufficient to source the volume of deltaic sediment (0.31 km^3) present in Sequence II. The flexural-margin river that occupied the Kazinga Channel during Sequence II time is the preferred source of sediments for the clinoforms.

As an alternative to a siliciclastic origin for the Sequence II clinoforms, we cannot rule out the possibility that they are composed of carbonate detritus developed atop the uplifted fault block. Coarse carbonate facies are well developed in some ancient rift-lake basins (e.g., Harris et al. 1994), and carbonate rich facies are observed in some localities in modern Lake Tanganyika (e.g., Cohen and Thouin 1987). However, large carbonate-dominated clinoforms are not well documented in lake basins, and virtually all marine prograding carbonate systems demonstrate a connection with a broad and shallow carbonate bank system, which generates abundant carbonate detritus that accumulates in the off-bank setting. The Edward progradational clinoforms are clearly isolated and have no affiliated carbonate-bank sediment factory, and accordingly we favor a siliciclastic origin for these deposits.

Beadle (1981) discussed the Pleistocene connection between lakes Edward and Victoria through the paleo–Katonga River, based on the geographic distribution of cichlid fish species. While a connection may have existed before rift-related surface uplift fully reversed the course of the paleo–Katonga River, it is unlikely that this river was the source of delta facies imaged in this study; the observed delta facies were probably deposited since the new drainage divide was uplifted and reversed some of the Katonga flow back toward Lake Victoria. The drainage area of the paleo–Katonga River is $\sim$ 29,300 km^2, which dwarfs analogue drainages such as the Dwangwa, Linthipe, and North Rukuru rivers found on the flexural margins of Lake Malawi (Wells et al. 1999). Additionally, the paleo–Katonga River potentially carried a high sediment yield, because it drained the highlands of southern Kenya associated with the Gregory rift (after Milliman and Syvitski 1992).

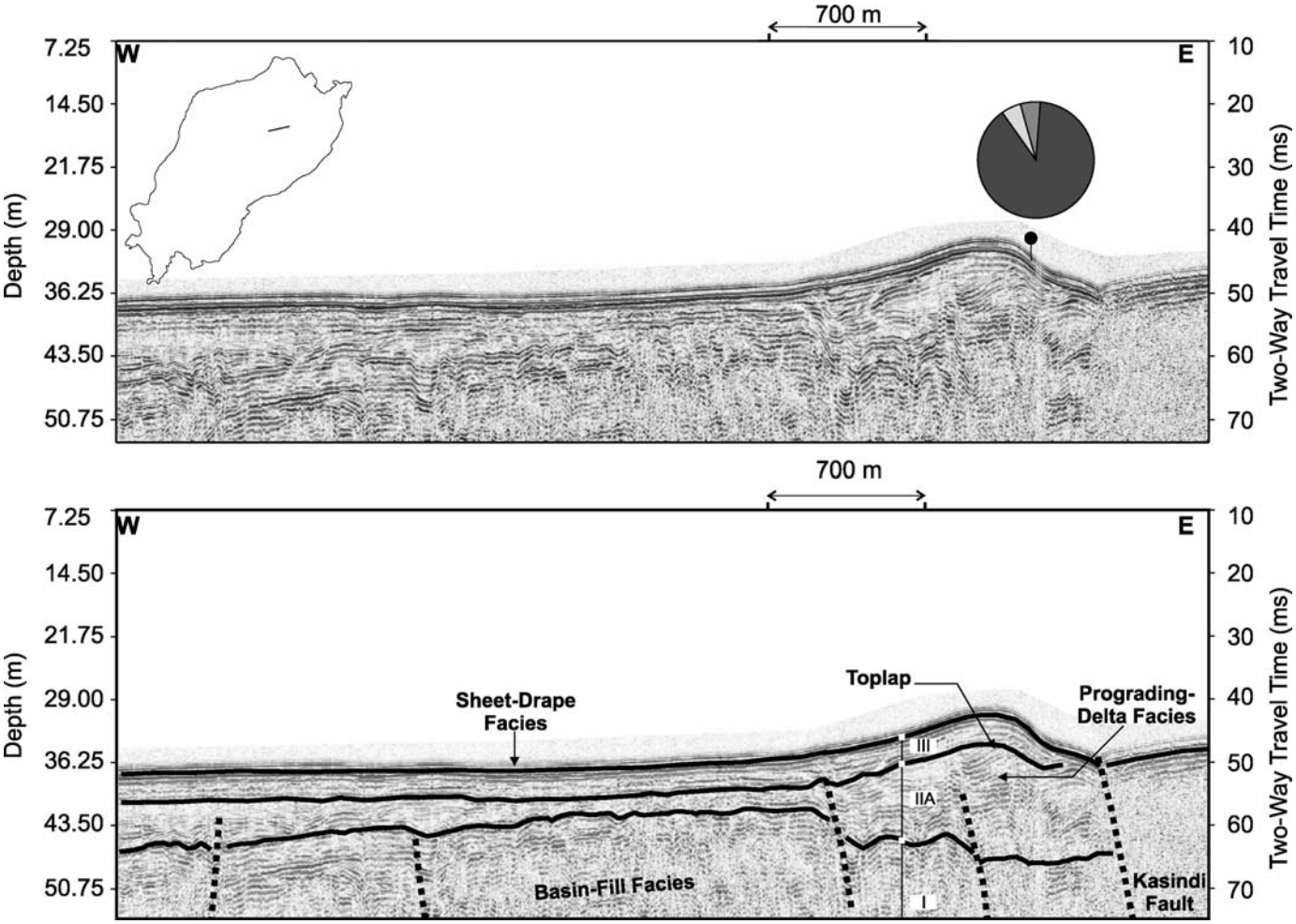


FIG. 9.—Seismic reflection line illustrating the seismic facies interpreted in this study. The upper panel is an uninterpreted section and contains flags and a pie chart marking the location of sediment grab samples. The grayscale of the pie chart illustrates the (sand + gravel)/silt/clay ratio, with coarser fraction represented by darker color. The lower panel is the same seismic reflection line with sequence stratigraphic interpretations. The vertical axes display both two-way travel time (right) and depth (left). Note the dominance of basin-fill facies in Sequence I. Basin fill occurs in Sequence I independent of location in the study, suggesting this time period in the history of the basin was marked by enhanced fault activity. Note also the focus of coarse sediment (coated ancient gastropods) coincident with prograding-delta facies. Drape facies adjacent to the deltaic sediments display a markedly different lithology and seismic character.

Prograding-delta facies imaged in Sequence II are interpreted to have formed in response to the basinward migration of the lakeshore and outflow from the Kazinga Channel. Using the topset-to-foreset transition as a proxy for paleolake level, we interpret a minimum base-level drop of ~ 37 m during Sequence II time. A study utilizing data from a sediment core collected in Lake Edward infers that the precipitation/evaporation ratio of the lake may have been reduced during the LGM, consistent with the interpretation of cool, arid environmental conditions during the deposition of Sequence II prograding-delta facies (Russell et al. 2003a). Lake level in Lake George is in effect controlled by the level of Lake Edward, with George outflow and desiccation following each –5 m regression of Lake Edward. The small clinoform imaged in Sequence III (Fig. 8), and interpreted as a prograding delta, is another example of a lowstand in Edward that probably corresponded to desiccation in Lake George. Timing for this event cannot be determined from this dataset, although we speculate deposition to have been coeval with a well-dated Holocene lowstand, ~ 2 ka (Russell et al. 2003a).

Sequence III strata interpreted to be prograding delta facies are not acoustically well resolved in the study area, making initial facies characterization somewhat difficult. However, sediment sampling at the toe of this feature recovered relict mollusks similar to those collected on top of Sequence II clinoforms (Fig. 11). X-ray diffraction analysis indicates that the mineralogical composition of these coated shells is dominated by manganese carbonate. Ferric ooids and Fe/Mn nodules have been observed in Lake Malawi and are believed to form in suboxic strata and precipitate when encountering oxic conditions at the sediment–water interface (Williams and Owen 1990; Owen et al. 1996). Russell et al. (2003a) discuss similar oolitic sands composed of iron and magnesium oxy-hydroxides and shallow-water gastropod hash as evidence for a late Holocene lowstand in Lake Edward. Thus we interpret the manganese shell coatings and presence of clinoforms in the seismic record as dual evidence for climatically forced lake-level change during Sequence III time. The gastropod shell blankets found in Lake Edward likely colonized bathymetric highs formed by lobate lowstand delta deposits, coeval with the ~ 2 ka regression event. Such bioclastic gravels are common in rift lakes, especially in shallow-water, high-energy environments (Cohen and Thouin 1987). Alternatively, the shell blanket could represent a condensed section, marking the onset of rising water levels in the basin. An unstable

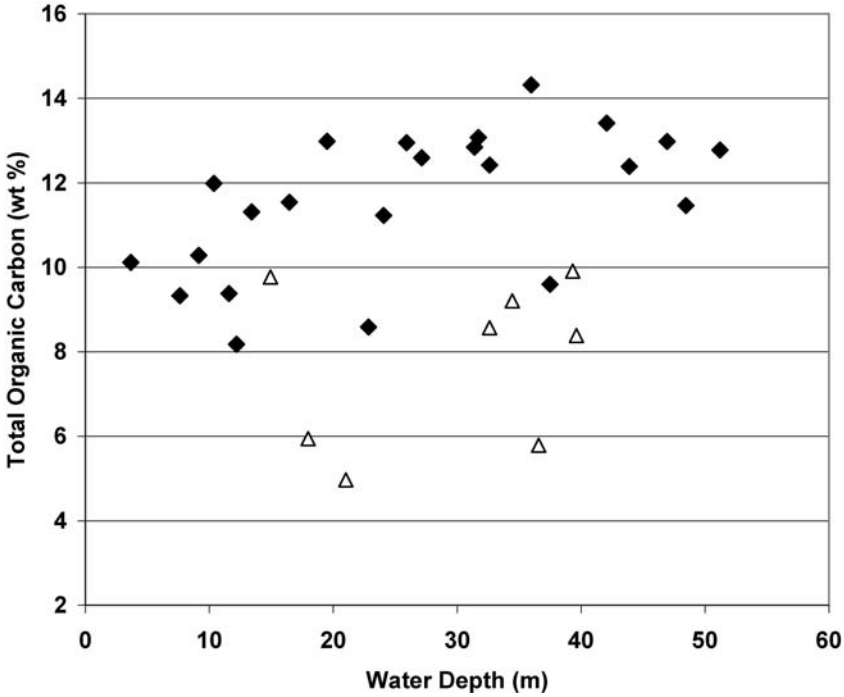


FIG. 10.—Total-organic-carbon values obtained for lake-bottom sediment samples collected in the study area. See Figure 2 for sample locations. Open triangles indicate values obtained on shell material associated with prograding-delta facies.

Holocene environment plausibly explains the coatings of these gastropods, as the position of the oxycline shifted with changes in lake level.

Sheet-drape facies reflect hemipelagic suspension deposition that onlaps or blankets preexisting features on the lake floor. Nonparallel sheet-drape reveals the influence of fault-controlled relief of the lake floor. Within the seismic stratigraphic framework, sheet-drape marks the youngest depositional interval. The mode of sedimentation during Sequence III time is dominated by hemipelagic sedimentation during relative lake-level highstands. Areas of sheet-drape observed in the study area appear unaffected by subaqueous mass wasting or erosion (Fig. 9). Significant breaks in sheet-drape uniformity within Sequence III are observed adjacent to the Bantu Fault and near the small clinoform package near the mouth of the Kazinga Channel, where seismic character becomes obscured but where reflections are observed to dip to the west (Figs. 4 and 8, respectively). Sheet-drape facies thin dramatically over the bathymetric high formed by the Bantu Fault, but remain ~ 3–5 m thick over the rest of the study area. Sediment sampling and analysis indicates that this facies is composed of fine-grained, organic-rich, hemipelagic sediments.

Implications of Lake-Level Change in Lake Edward

Major events in the evolution of Lake Edward and its recent depositional history are summarized in Table 2. Significant lake-level lowstands are suggested by Sequences II and III, but lake-level conditions cannot be accurately constrained from the lowermost depositional sequence. Importantly, both regressions interpreted in this study force basin closure, due to shallow sill depths at the Semliki River outlet. Ramifications of the hydrologic closure of Lake Edward are significant also for Lake Albert, inasmuch as discharge from the Semliki River constitutes the second-largest fluvial input to that basin (Said 1993). Additionally, the ecology of endemic species such as cichlid fish utilizing the pathways connecting the basins must have been dramatically altered due to basin closure, a phenomenon debated in other regions of the UNW (Johnson et al. 1996; Meyer et al. 1996; Verheyen et al. 2003).

Our estimate of an LGM age for the Sequence II progradational clinoforms is based on the extrapolation of sedimentation rate data (Russell et al. 2003a) to the Sequence I–II boundary (e.g., Figs. 4–6). Such a severe lowstand at the LGM is consistent with aridity elsewhere in the UNW at this time, including the desiccation of Lake Victoria (e.g., Johnson et al. 1996; Scholz et al. 1998; Stager et al. 2002), and the near-desiccation of Lake Albert (Beuning et al. 1997). While the lake lost ~ 65% of its water volume during Sequence II time, much of the deep basin, downdip of the delta system and west of the Bantu Fault escarpment, probably remained subaqueous during this period of high-latitude cooling and tropical aridity. That Lake Edward escaped desiccation during this interval may be a consequence of steady runoff from the Ruwenzori Massif, and the Blue Mountains of the DRC (e.g., Fig. 1). Lowstands in lakes Tanganyika and Malawi are also interpreted at the LGM (Gasse et al. 1989; Johnson et al. 2002). The deep-basin strata in Lake Edward may house the only continuous record of tropical climate change in the UNW for the late Quaternary period.

Because the age of the Sequence I–II surface is estimated by extrapolation, we cannot rule out the possibility that the interpreted delta clinoforms are in fact older, and that the LGM estimate is a minimum age for the package. Similar lowstand delta packages have been identified in Lake Malawi (e.g., Scholz 1995) and Lake Tanganyika (Scholz et al. 2003) and appear likely to date from Marine Isotope Stages 4, 5, or earlier. Because the clinoforms are incongruously uplifted relative to the adjacent muddy facies, it appears that the Bantu and Kasindi faults may have been active for some time interval following the cessation of clinoform deposition.

SUMMARY AND CONCLUSIONS

Over 200 km of digital single-channel seismic data, coupled with 33 lake-bottom sediment samples, were collected offshore of the Kazinga Channel on Lake Edward, Africa, to investigate shallow-water facies development and depositional processes along the flexural margin of this rift lake.

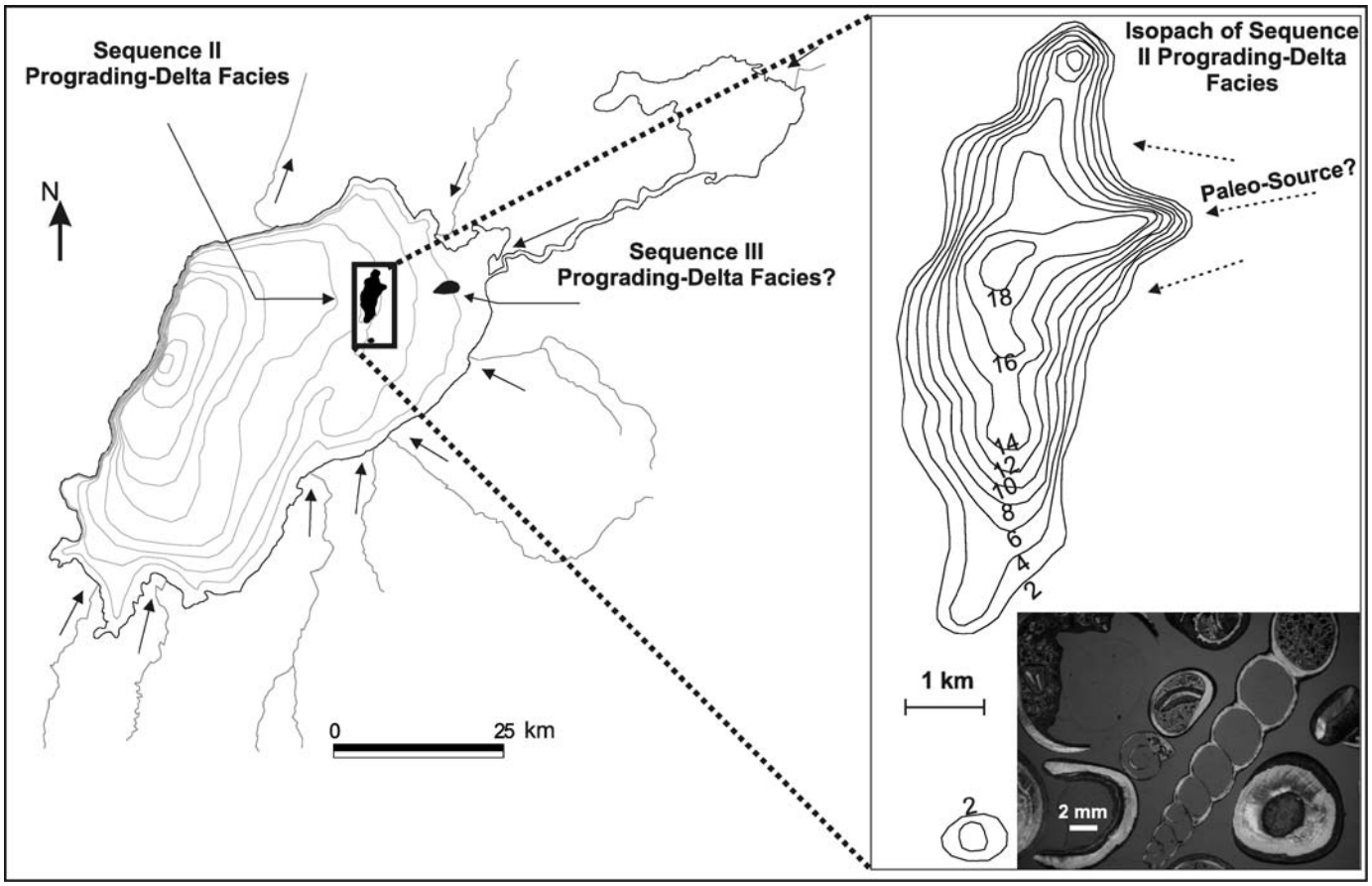


FIG. 11.—Bathymetric map showing location of prograding-delta facies interpreted on the flexural margin of Lake Edward. Inset map shows an isopach map of the larger Sequence II prograding-delta facies complex, which reaches a maximum thickness of 18 m. The deposit is capped by a gastropod shell lag. Based on the modern hydrology of the basin and the fan shape (plan view) of the deposit, we interpret the Kazinga Channel to be the source of these deltaic deposits.

Three seismic sequences are identified in the single channel data, and are named the Konjo Sequence Set. Climatically driven lake-level change appears to control sequence development, based on top-discordant (onlap and erosional truncation) and bottom-discordant (downlap) relationships observed in the study area. The minimum lowstand occurring in Sequence II time was ~ 37 m below the modern lake surface, and the minimum lowstand in Sequence III time was ~ 18 m below the modern lake surface. Although the exact timing of these lowstands remains to be determined through future sediment coring and age dating, we speculate that the Sequence II lowstand occurred in the late Pleistocene, possibly at the time of the LGM, and that the Sequence III lowstand was a late Holocene event.

Four seismic facies types are identified from the single-channel seismic reflection and grab-sample data: (1) sheet-drape facies; (2) prograding-delta facies; (3) basin-fill facies; and (4) slope-front-fill facies. Basin-fill facies predominates in the lowest depositional unit and is the most volumetrically significant facies within the study area. The dominant controls on the development of these facies types are extensional tectonics, climate (lake level) change, and lake-margin physiography.

Prograding delta facies form due to the interplay between climate-driven lake-level change and the lake-margin physiography created by the connection of Lake Edward to the Kazinga Channel incised-valley system. During lowstand times, sediment-laden flows drain Lake George, using the Kazinga Channel as a confining conduit, across the flexural margin of Lake Edward. Based on the dipping reflections in Sequence II prograding-delta facies, the sediment flows from the Kazinga Channel appear to have been sufficient to transport coarse-grained sediment. When highstand conditions returned to Lake Edward, the Kazinga Channel and Lake George acted as sediment traps, limiting sedimentation on the flexural margin to the steady rain of hemipelagic sediment, forming sheet-drape facies offshore and deltaic deposits adjacent to small river drainages.

Two scales of tectonic deformation control the occurrence and distribution of the other acoustic facies in the study area. Intrabasinal fault orientation and subsidence controls the location of slope-front-fill facies and the basin-fill facies. In addition, secondary faults in the study area lack growth strata, suggesting that major displacements occurred recently in the history of Lake Edward. Because the Kasindi Fault bounds major Sequence II clinoforms, we interpret this fault activity to largely postdate clinoform deposition, rising water levels, and the transition to Sequence III time. Surface uplift outboard of the rift proper reversed the drainage direction of the paleo–Katonga River and helped to form the modern drainage basin of Lake George, providing an extrinsic control on the formation of prograding-delta facies in the basin.

The results of this study support the concept that, because of its depth, Lake Edward did not dry out during the Last Glacial Maximum and may

TABLE 2.—*Summary chart highlighting major events in the history of Lake Edward, East African Rift.*

Event	*Evidence*	*Control Mechanism*	*Approximate Age*	*References*
Sequence III	• Basal onlap • Small channel-mouth clinoforms • Calcite in sediment cores	Climate change	late Holocene (~ 2 ka)	This study; Russell et al. 2003a, 2003b
Early Holocene highstand	• Moist pollen species in sediment cores	Climate change	early Holocene	Beuning and Russell 2003
Lowering of the Semliki Sill	• Shallow sill depth • Rapids and recent incision at sill • Terraces 14 m above modern river	Extensional tectonics	Terminal Pleistocene (~ 11–9 ka?)	Beadle 1981; Laerdal and Talbot 2002; Russell et al. 2003a
Sequence II	• Upper bounding surface defined by toplap; basal downlap • Prograding delta facies	Base level change associated with the LGM	LGM/late Pleistocene?	This study; Russell et al. 2003a
Bantu and Kasindi Faulting	• Active normal faults displacing the water-bottom reflection • Kasindi Fault bounds the extent of Sequence II clinoforms to the east • Faults lack growth strata	Extensional Tectonics and base level change	Major movement during Sequence II lowstand likely	This study; Laerdal and Talbot 2002
Sequence I	• Upper bounding surface defined by downlap-truncation • Basin fill dominant	Extensional tectonics	Pleistocene	This study; Laerdal and Talbot 2002
Erosion of the Kazinga Channel	• Deeply incised channel valley with high scarps	Base-level change in L. Edward	Numerous scour events occurred during the basin's history	
Volcanism proximal to L. Edward	• Virunga Volcanoes • Toro Ankole Explosion Craters	Extensional tectonics	Cenozoic (Virunga: ~ 11 Ma; Toro Ankole: ~ 50 Ka)	Boven et al. 1998
Flooding of L. George	• Lake George Basin, lacking classic half-graben geometry	Extensional tectonics	Pliocene–Pleistocene?	Bishop 1969
Major drainage reversals in the Upper Nile Region	• Reversed Katonga, Kagera, and Kafu Rivers • Upwarped topography in western Uganda	Extensional tectonics	Miocene?	Beadle 1981; Kendall 1969
Rift Shoulder Uplift, formation of L. Edward	• Lubero Border Fault • L. Edward rift basin	Extensional tectonics	Miocene?	Bishop 1969; Ebinger 1989

house the only continuous late Quaternary record of environmental change in this part of East Africa. Consequently, it may be a desirable site for future scientific drilling and further seismic reflection acquisition.

ACKNOWLEDGMENTS

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