RIFT LAKES OF EAST AFRICA

New Seismic Data and Implications for Future Research

by B.R. Rosendahl and D.A. Livingstone

Current seismic studies of East African Rift lakes are leading to new ideas on the early stages of rift basin development. Vertical reflection profiling of Lake Tanganyika indicates the presence of >3 000 m of sediment and suggests an age for the lake no younger than Lower Miocene. Some parts of Lake Malawi may also be that old. Both lakes are structurally complex, consisting of several distinct basins each composed of many individual blocks. The basins are the fundamental structural units of the African Rift, but they are neither synchronous nor chronologically systematic in their development. Sediments of oceanic thickness have been deposited in basins less than 80 km wide, resulting in facies packages with aspect ratios of 1:1. Seismic studies are continuing, and will be extended to other major lakes of the African Rift. These surveys provide a new insight into the process of continental break-up, and may serve as a galvanizing force in the recovery of a very detailed 20 Ma record from one of East Africa's rift lakes.

Background

Interpretations of the archaeological, climatological and palaeoecological records of East Africa are intricately linked to the geological history of the East African Rift. This history also has an important bearing on many geologic concepts, especially those involving continental fragmentation and the early stages of ocean basin evolution.

Unravelling the geological story of the East African Rift has been difficult because large expanses of the Rift are covered by lakes. Two of these, Malawi and Tanganyika, comprise a system which extends over a length of 1200 km (Fig. 1). Compared to other bodies of water with equivalent geological significance, these lakes have been studied by only a few researchers (e.g. Andrew, 1974; Chorowicz et al., 1979; Crossley and Crow, 1980; Crow, 1980; Degens et al., 1971; Dixey, 1926, 1956; Hecky, 1978; Livingstone, 1965; Sutton and Berg, 1958; von Herzen and Vacquier, 1967; Wong and von Herzen, 1974).

In a search for deep targets for scientific drilling we have begun a systematic geophysical investigation of the main rift-valley lakes of Africa (Cromie, 1982). The cover of this issue shows the R/V NYANJA, the nucleus of our geophysical efforts in East Africa. NYANJA will spend the next three years conducting geophysical surveys of the great rift-valley lakes of East Africa. A mere 11 m in length and displacing only 10 tons, the boat houses a modern 48-channel seismic system with a 1000 m-long hydrophone streamer (Fig. 2), high-resolution seismic systems, side-scan sonar, echo sounder, marine magnetometer and a plethora of navigational devices such as single and dual channel satellite navigators, radar and an automated course plotter. NYANJA has been specially built to fit into the cargo bay of a Boeing 747 (Fig. 3) and to be transported over rough roads.

To date we have collected about 4000 km of single-channel reflection profiles from Lakes Malawi and Tanganyika (Fig. 4). We present first some of the highlights of this investigation and then describe what is planned for the next three years of field study.

Inter-Lake Comparisons

The waters of Lakes Malawi and Tanganyika cover areas of great structural complexity. The seismic profiles reproduced

Figure 1: The rift valley system of East Africa, showing major lakes numbered as follows: 1-Malawi; 2-Rukwa; 3-Mweru; 4-Tanganyika; 5-Kivu; 6-Edward; 7-Mobutu Sese Seko; 8-Turkana; 9-Victoria; 10-Natron.

Figure 2: Using a 1000 m-long multichannel streamer on Lake Tanganyika (Photo by C. Ebinger).

here give some indication of this on the local scale, and Figure 5 shows the complexity on the scale of a whole lake.

Neither lake is a natural structural unit — such units occur on the smaller scale of basins within each lake — but there are some general similarities and differences between the two. The major similarity is that both lakes were formed by tensional forces which created main axial grabens bordered by large gravity faults, as shown long ago by Gregory (1896).

The main border faults of both lakes (Fig. 6) are influenced by the type and trend of the basement, in the same way that the rift bifurcates around the Tanganyika craton (Fig. 1). The primary difference between the two lakes is shown by contrasts in the geometries of the axial grabens, which may result from differences in the orientation of the tensional regime.

Lake Malawi seems to be characterized by half-grabens like those shown in Figure 7, with the main border faults developed on the western side. Although this geometry describes much of Lake Malawi, a reversal (i.e. deep side on the east) occurs in the northern quarter of the lake. In contrast, Lake Tanganyika is characterized by full grabens with well-developed border faults on both sides. Profiles of the main north basin of this lake (Fig. 8) also show an axial dome within the full graben. The full graben form tends to become bowl-shaped in section as sedimentation progresses, covering the dome.

Half grabens occur in the main kink (dog-leg) region of Tanganyika and full grabens may occur in the southern end of Malawi, but there is a general tendency toward one style or the other in each lake. This difference could be a reflection of the importance of uplift relative to pure extension in the development of rift grabens, with uplift predominating in Malawi and extension in Tanganyika. Uplift may evolve into extension as a rift ages, as implied by Dixey (1956), and the axial dome in Tanganyika may be a remnant of its juvenile uplift phase. Another explanation now being considered by our research team relates this difference to the proportion of shear involved in the rifting process (i.e. amount of oblique rifting); the greater the component of shear the higher the propensity towards half grabens. Our axial transects in Malawi show much more faulting and folding than their Tanganyika equivalents, supporting the contention that shearing is generally more pervasive in Lake Malawi.

Concept of the Fundamental Rift Parameter

Perhaps the most exciting and far-reaching result of our surveys is the emerging concept of what we have termed the "fundamental rift parameter." This idea has evolved out of the observation that Malawi and Tanganyika are divided into natural structural units with a certain dimensional repeatability. The units are generally parallelogram-shaped in plan

and basinal in section. Typical dimensions are 50-70 km long by 20-40 km wide. Boundaries between units usually coincide with changes in boundary-fault orientations and are often expressed as sills or regions of uplifted basement, especially where dog-legs occur in the lakes.

In spite of their similar sizes and shapes, these structural units are not necessarily produced by the same stress fields with the same orientations, nor are they of the same age or even systematic in their chronological development within a lake. It appears that rifting does occur with predictable and repeatable dimensions in these lakes regardless of the stress field or time of fracturing. Indeed, the literature on rift and pull-apart basins shows that this sort of scaling may be applicable to juvenile rifts in general, and in particular to those which have developed in old cratonic regions.

If this idea is correct, then it gives considerable insight into the evolution of rift lakes and rift zones. The kinks or dog-legs in the lakes are a manifestation of a dimensional limitation, forming where subparallel segments of fundamental rift length are close enough together in space to be connected by shear zones (pre-transforms?). Rifts form as a result of coalescence of these segments within a width-restricted band. The success or failure of a rift may depend upon how closely in space and time adjacent segments develop. We assume that there is a distance beyond which the available rifting energy will not permit coalescence within or between rift basins, and that the greater the time difference between rifting events, the less likely it is that spatial proximity can be maintained.

There are two possible explanations for the fundamental rift parameter. The first contends that the rifting forces are regional and uniform and attributes spatial repeatability to the influence and effects of a pre-existing grain imposed by different kinds of basement. The second argues that the causative agents of rifting are localized and three-dimensional (e.g. mantle plumes) during the initial stages of rifting and become progressively more regional as coalescence of fundamental units continues. We favour the second explanation but utilize the first to explain some of the spatial variability between fundamental rift units.

Even within basins of fundamental size, great structural complexity can occur. This is especially apparent in Lake Malawi. Figure 9 shows a profile that is nearly perpendicular to that shown in Figure 7. There is as much faulting and folding in this longitudinal orientation as there is across the basin. Much of this deformation is apparently a consequence of shearing produced by extremely oblique rifting. As the end result, basins are formed composed of many small, parallelogram-shaped grabens and horsts, defined by normal faults on their eastern and western sides and strike-slip faults on their northern and southern edges. The expression "blocks within basins within lakes within rift zones" summarizes our structural results to date.

Stratigraphy and Sedimentation

No part of our seismic program has been more interesting than its acoustico-stratigraphic aspect, and none more difficult. The reason for this difficulty is so intriguing in its own right that we present it here.

Figure 3: NYANJA after off-loading at Heathrow airport (Photo by C. Ebinger).

Figure 4: Seismic reflection profiler coverage on Lakes Tanganyika (A) and Malawi (B).

From the stratigraphic and sedimentological perspectives, Lakes Malawi and Tanganyika can be viewed as miniature oceans, for they contain most of the components associated with continental margins, including shelf-sediment wedges, deltas, submarine fans, turbidites and slumps. They also show many of the features associated with open ocean sedimentation, such as deep basins, biogenic oozes, anoxic environments and even contourites. The difficulty arises because all these components are squeezed into widths of less than 80 km. Facies changes that ordinarily occur on the scale of hundreds or thousands of kilometers in the oceans occur over distances of a few kilometers to tens of kilometers in these lakes. A complicating factor is that the thicknesses of sedimentary packages can be comparable to that in the oceans, and in some places the thickness of a single facies exceeds its length in cross section. The end result can be facies packages with aspect ratios of 1:1.

Other factors complicate the picture further. The first is the effect of morphology on depositional patterns, particularly the influence on lateral continuity of the "block within basin" morphology discussed earlier. Second are the enormous changes in amplitude of reflection, presumably due to very high and variable organic contents of the sediments and possibly to the local occurrence of hydrocarbons. The third factor is the likely presence of hydrothermal effects in the sediments, especially around faults. A fourth is the occurrence of unconformities in the sections.

Understanding how all these factors come together to produce the acoustic signatures observed is changing the way we interpret seismic data from the lacustrine portions of rift

Figure 5: Structural map of Lake Malawi and surrounding area, compiled from many sources by C. Ebinger. Lake structures trending oblique to the main N-S orientations are interpreted as shear faults. The modern NE-SW faults shown have strong strike-slip components. Many others too numerous to show are present but are difficult to orientate between profile lines.

Figure 6: The Tanzanian shore of Lake Tanganyika. The fault scarps that comprise the shoreward faces of the rift shoulder continue an additional 1000 m below the lake surface (Photo by P. Lorber).

basins (Fig. 10). Based on our seismic work to date, together with some piston core and outcrop information, the following picture can be drawn. Main reflectors tend to be basin-wide and probably constitute depositional pulses (or breaks) stemming from tectonic events. Acoustic facies packages tend to be spatially variable, especially those perpendicular to the main axis of the lake, and they often cross main reflectors. The dominant facies change is interpreted to be that between biogenic (pelagic) organic-rich sediments and clastics of terrigenous origin. The biogenic facies tends to be acoustically "transparent" in the ooze state, but becomes highly stratified as it goes to organic shales with depth. The terrigenous clastic facies includes many sub-facies (e.g. deltaic, submarine fan, turbidite), all of which tend to produce strong and highly reflective events at shallow depths.

With burial, these subfacies tend to disappear from the seismograms, probably due to their seismic impenetrability. If we now introduce some of the complications mentioned above, such as hydrothermal circulation cells, block-within-basin morphology and unconformities, then it is not hard to appreciate why the simple two-facies model results in interpretations as complex as that in Figure 10.

The relatively great sediment thicknesses are startling. More than 3000 m of sediment occurs in the north basin of Lake Tanganyika (Fig. 8) and probably more than 1000 m in the central sections of Lake Malawi. Measured late-Quaternary accumulation rates (e.g. Degens et al., 1971; Livingstone, 1965) and estimates of compaction, indicate that the basal sediments in the north basin of Tanganyika are unlikely to be younger than Lower Miocene in age. Considering the amount of section missing above the angular unconformity shown in Figures 7 and 10, Miocene ages for Lake Malawi are also plausible.

Depositional basins seem to have been in existence at least intermittently since Mesozoic time, for we have strong evidence in Malawi that Karroo troughs continue across the lake at two locations (Fig. 5). We suspect that reoccupation of Karroo basins may be a relatively common phenomenon in these great rift-valley lakes; if so, they do not have singular ages of formation.

The Next Three Years

During the fall of 1982, NYANJA carried out reconnaissance surveys of the southern half of Lake Tanganyika plus a grid survey of the main north basin. Surveys are planned for Lakes Turkana, Kivu, Mobutu Sese Seko, Victoria and portions of Lake Malawi in the spring and summer of 1983, and for the rest of Lake Malawi plus Lakes Rukwa, Eyasi and Natron in 1984. Lakes Edward and Mweru are possible additions.

The ultimate purpose of these surveys is to decipher the geologic history of the East African Rift, but the work has many objectives involving several disciplines. Some of these are to:

- continue the search for drilling sites which are very likely to yield detailed and precise records of climatic changes over the last 10 Ma or more of earth history;
- ascertain the applicability and usefulness of tectonic and depositional models of the rift lakes, especially in terms of our understanding of the break-up of continents and the early evolution of passive margins;
- test the concept of the fundamental rift parameter and define the scales that apply to individual rift-basin models;
- provide a geologic framework for anthropologic studies of hominid evolution.

NYANJA's capabilities give us considerable flexibility in matching seismic methodologies to study area and objectives.

Figure 7: Seismic reflection profile from Nkhata Bay (N on Fig. 5) to Likoma Islands, Lake Malawi. Profile can be considered a cross-section of the Malawi Rift in the vicinity of 12° S. Vertical scale in seconds of two-way reflection time. Horizontal extent about 70 km.

Figure 8: Seismic reflection profiles of the main north basin of Lake Tanganyika. Profiles can be considered cross-sections of the Rift between about 4°30'S (top left) and 5°20'S (bottom right). Vertical scales as for Figure 7. Horizontal extent about 45 km.

Grid surveys on the larger lakes will be conducted in multi-channel CDP format in 24- or 48-fold configurations, using airgun sources and a 1000 meter long "mini-cable." Reconnaissance surveys on the larger lakes will be conducted in either multichannel CDP or single-channel, normal incidence format, depending upon location, objective and geology. High-resolution seismics along with side-scan sonar and magnetics data will be collected along many tracklines. For some locations, such as Lake Turkana, special surveys have been designed around these methods.

Several complementary programs are planned as well. A group of geologists under the supervision of Dr. Jacques LeFournier of the ELF-Aquitaine will continue sampling and mapping programs in and around the rift-valley lakes. In 1981 this group studied portions of Lakes Tanganyika and Rukwa, and a return expedition is planned for 1983. LeFournier's group is now working on Lake Malawi. Livingstone and his co-workers will continue their pollen, diatom and grass cuticle analyses of piston cores representing the last 10 000 to 100 000 years.

Finally there is CEGAL (Climate, Evolution and Geodynamics of African Lakes). CEGAL is a multidisciplinary and international project whose ultimate objective is to raise a long core from one of the rift-valley lakes of Africa (Lewin, 1981). Such a core might very well span 10 or 20 Ma of earth history and should contain a relatively continuous and precise record of climatic fluctuations. The value of this core would be immeasurable by scientific standards – and so will be the expense! Estimates of the cost to obtain a continuous core through the sedimentary section in the main

north basin of Tanganyika are of the order of \$30 million or more. For this reason, CEGAL probably will begin modestly with an attempt to raise a core spanning one million years from Lake Bosumtwi in Ghana.

Figure 9: Seismic reflection profile of the Nkhata Bay Province of Lake Malawi. Vertical scale as for Figure 7. Horizontal extent about 25 km.

Figure 10: Acoustico-stratigraphic interpretation of reflection profile shown in Figure 7. Based on many tape replays at different filter settings and different amplitude preservations.

The cost of CEGAL drilling on Tanganyika or Malawi is not prohibitive by petroleum industry standards. Indeed, we envision achievement of CEGAL's ultimate objective through a cooperative arrangement between science and industry. The greatest scientific impact of our geophysical work may, therefore, come only after the industrial drilling in the rift-valley lakes now being considered.

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ABOUT THE AUTHORS:

Bruce R. Rosendahl is an Associate Professor of Geophysics (Department of Geology, Duke University, Durham, North Carolina 27708, U.S.A.). His research activities center around the structure, dynamics and evolution of accretionary plate boundaries. He has participated in many oceanographic expeditions and is now engaged in developing the African Lakes geophysical project described in this article.

Daniel A. Livingstone, James B. Duke Professor of Zoology, at Duke University, is a biologist with a lifelong interest in geochemistry and Quaternary geology. After early work in embryology, zoogeography and fisheries he turned to the palaeoecology of Alaska and Nova Scotia. He has been studying African lakes and their sediments since 1962 and is now organizing Project CEGAL.