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The Structural and Stratigraphic Evolution of Lake Tanganyika

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ABSTRACT : Seismic data from Lake Tanganyika indicate a complex tectonic, structural, and stratigraphic history. The Lake Tanganyika rift consists of half grabens which tend to alternate dip-direction along the strike of the rift. Adjacent half-grabens are separated by distinct accommodation zones of strike-slip motion. These are areas of relatively high basement, and are classified into two distinct forms which depend on the map-view geometry of the border faults on either side of the accommodation zone. One type is the high-relief accommodation zone which is a fault bounded area of high basement with little subsidence or sediment accumulation. These high-relief areas probably formed very early in the rifting process. The second type is the low-relief accommodation zone which is a large, faulted anticlinal warp with considerable rift sediment accumulated over its axis. These low-relief features continue to develop as rifting processes. This structural configuration profoundly influences depositional processes in Lake Tanganyika. Not only does structures dictate where discrete basins and depocenters can exist, it also controls the distribution of sedimentary facies within basins, both in space and time. This is because rift shoulder topography controls regional drainage patterns and sediment access into the lake. Large fluvial and deltaic systems tend to enter the rift from the up-dip side of half-grabens or along the rift axis, while fans tend to enter from the border fault side.

INTRODUCTION

Lake Tanganyika is located along the western arm of the East African rift system between Lakes Kivu and Malawi (Fig. 1). Tanganyika is 650 km long, up to 80 km wide, and as much as 1.5 km deep. Its great depth coupled with its size makes it the largest lake, by volume, in Africa.

Traditionally, continental rifts have been regarded as full-grabens with little structural variation, and stratigraphic models for rifts have been developed upon that geometry. However, the present study indicates that the geometry of the Tanganyika rift is more complex than previously recognized. This has forced a reevaluation of the structural and stratigraphic evolution of the Tanganyika rift, and of continental rifts in general (Ebinger *et al.*, 1984; Rosendahl, Livingstone, 1983).

Project PROBE (Proto-Rift Oceanic Basin Evolution) of Duke University's department of Geology in North Carolina, USA, collected more than 2000 km of multichannel seismic reflection data from Lake Tanganyika (Fig. 2). These data were acquired aboard the R/V NYANJA using a 48-channel hydrophone streamer and a single, 140 cubic-inch airgun. Seismic lines were processed at project PROBE's computing facility. All profiles have been stacked at 24-fold, and the dip lines are shown in migrated format.

The seismic lines were shot with an average distance between dip lines of 12 km. This line density is adequate for understanding the large-scale structure and stratigraphy of Lake Tanganyika.

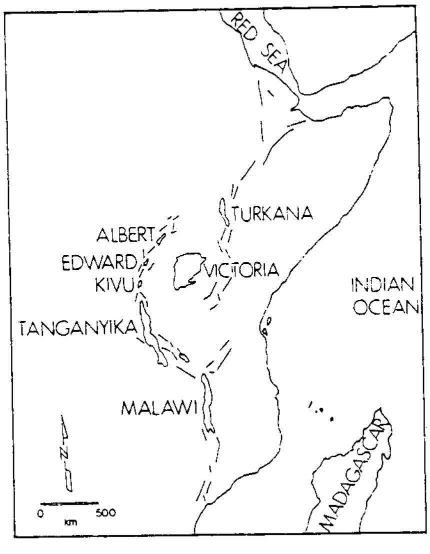

Fig. 1. The location map of Lake Tanganyika.

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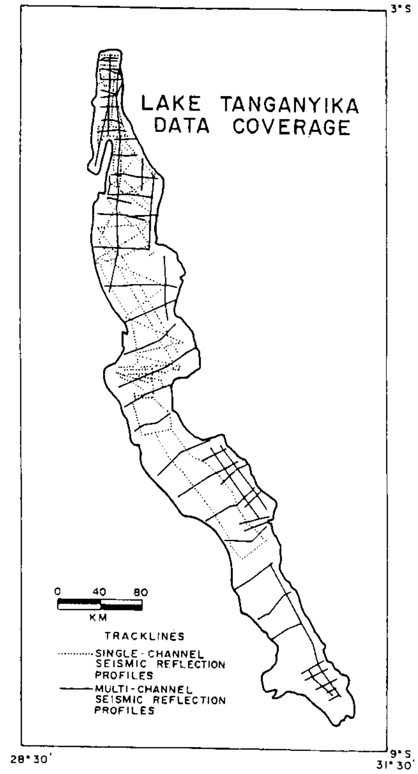

Fig. 2. Multifold seismic coverage of Lake Tanganyika.

Because the rift is well developed, fault patterns and depositional sequences are usually obvious. Another benefit of studying this lake is that there is not enough diapirism or igneous intrusion to obscure these depositional pattern.

STRUCTURAL RELATIONS

Lake Tanganyika is composed of individual structural units linked together in various ways (Fig. 3). All of these units are half-grabens with typical widths and lengths of 40 and 110 km, respectively. There is usually one dominant system of normal faults bounding each half-grabens; the throw on these fault systems can be as much as 6 km. Large normal faults also can occur on the shoaling side of half-grabens, but these are subordinate to the major bounding faults and usually antithetic (dipping in the opposite direction) to them (Fig. 4, line 212). Most half-grabens are internally faulted, and in many cases the major internal faults are synthetic (dipping in the same direction) to the master border faults. There appears to be an inverse relationship between the intensity (i.e. frequency) of internal faulting and the amount of subsidence. The more deeply subsided half-grabens tend to display the least internal fracturing (e.g. compare line 212 with line 106, Fig. 4). There is even some indication that the intensity of internal faulting increases toward the shoaling sides of the individual half-grabens (Fig. 5, line 208). It should also be noted that the true form of the border faults is usually masked by either acoustically transparent or chaotic facies. These facies probably represent fanglomerate wedges or piles of acoustically homogeneous talus shed directly from the border fault escarpment. This masking effect makes it difficult to characterize the complexity of the border fault systems.

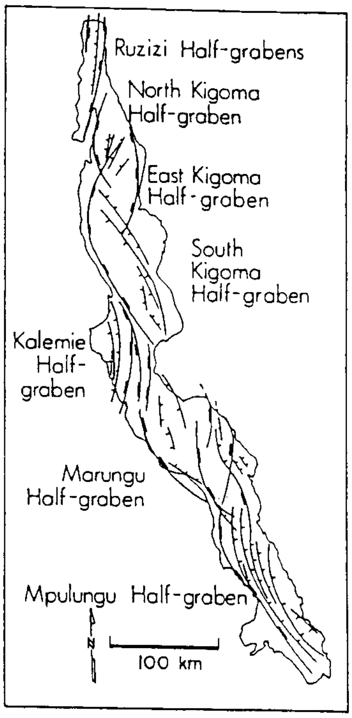

Fig. 3. Simplified tectonic map of Lake Tanganyika.

Fig. 3 illustrates that the spacial distribution and linking of half-grabens is very complex. Along the strike of the lake, the locations of the major bounding fault systems tend to alternate from one side of the lake to the other. Boundaries between adjacent half-grabens are of two general types. Either a transverse fault intersects the rift at an oblique angle, or the border fault curves toward the rift axis and becomes a strike-slip fault system which gradually dies out toward the opposite side of the rift (Fig. 3).

These distinct zones, interbasinal ridges and hinged highs, of strike-slip faulting which separate adjacent half-grabens were termed by Rosendahl (1983, 1987) as "accommodation zone," because these are zones

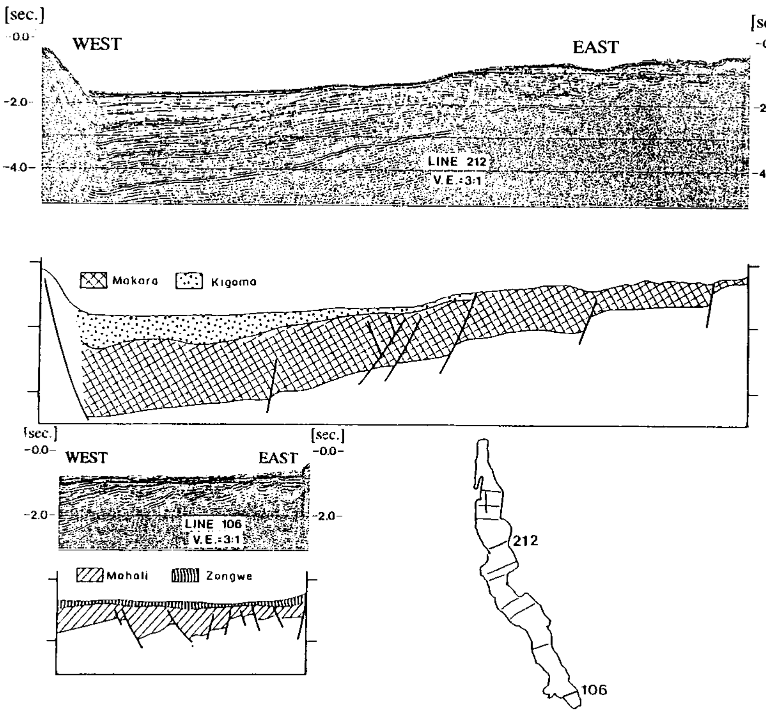

Fig. 4. Multichannel seismic profiles and interpreted cross-sections of line 212 and 106.

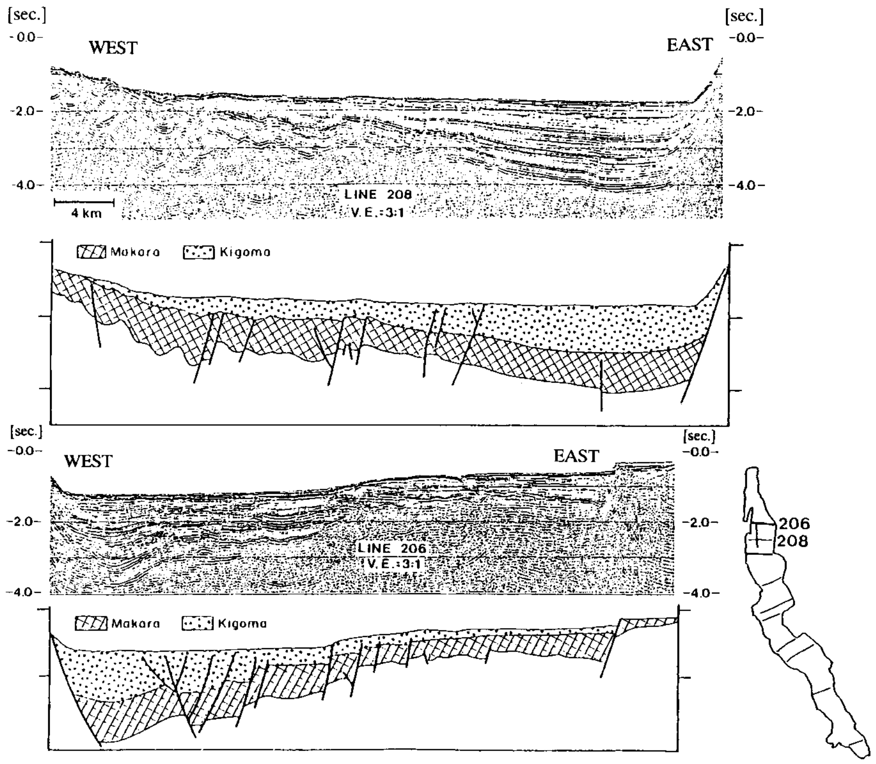

Fig. 5. Multichannel seismic profiles and interpreted cross-sections of line 208 and 206.

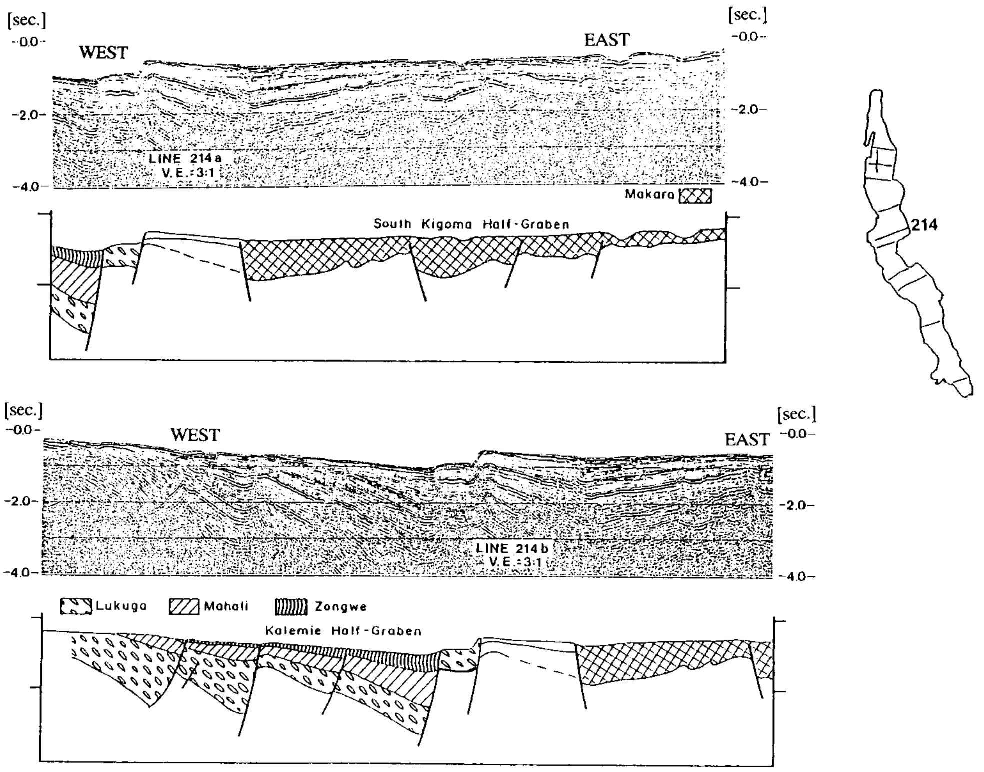

Fig. 6. Multichannel seismic profiles and interpreted cross-sections of line 214: seismic profile of line 214a is a right portion of track 214 and line 214b is a left portion of track 214.

where translational motion compensates for crustal extension along the normal faults which either bound or are within each half-graben. Accommodation zone has two distinct geometries (Fig. 8). They can link two overlapping half-grabens such as the East and South Kigoma half-grabens (Fig. 3). In this case the accommodation zone takes the form of an anticline (Fig. 7). This type of geometry (Fig. 8a) creates what is termed a low-relief accommodation zone because there is usually very little bathymetric relief on the lake floor over these features. High-relief accommodation zone is formed by two border faults curving toward each other from opposite directions (Fig. 8b). An example of this type of accommodation zone is the linking geometry between the South Kigoma and Kalemie half-grabens (Fig. 3). In this situation the accommodation zone comprises two distinct fault systems which bound relatively unsubsided basement ridges (Fig. 6, line 214).

Another complexity in the geometry of half-grabens and accommodation zones is that half-grabens not only dip toward major border fault systems, but also plunge along their strike. Adjacent half-grabens can either plunge toward or away from each other. In the former case (e.g. East and South Kigoma half-grabens, Fig. 3) the accommodation zone between these basins is not a pronounced bathymetric feature and is considered to be a low-relief accommodation zone. The strike-slip character of low-relief accommodation zones often can be seen on seismic data, in some cases they may appear as negative flower structures or vertical faults (Fig. 7, line 220). An important consequence of overlapping half-grabens is morphologically a full-graben, although the genetic structural units are half-grabens. Thus, the basic structural configuration of Lake Tanganyika is series of half-grabens whose dip-directions tend to alternate along strike. The boundary between adjacent half-grabens is an accommodation zone that is either high or low relief.

Another important observation is the shape differences of half-grabens. In the northern half of the lake (Fig. 3, Kalemie half-graben and north), each half-graben is an elongate trapezoid with an arcuate border fault system, while those farther south look like rhombs. The change in shape seems to correspond to the intersection of the rift with an onshore Permian rift basin (Fig. 9), which probably continues beneath the southern part of Lake

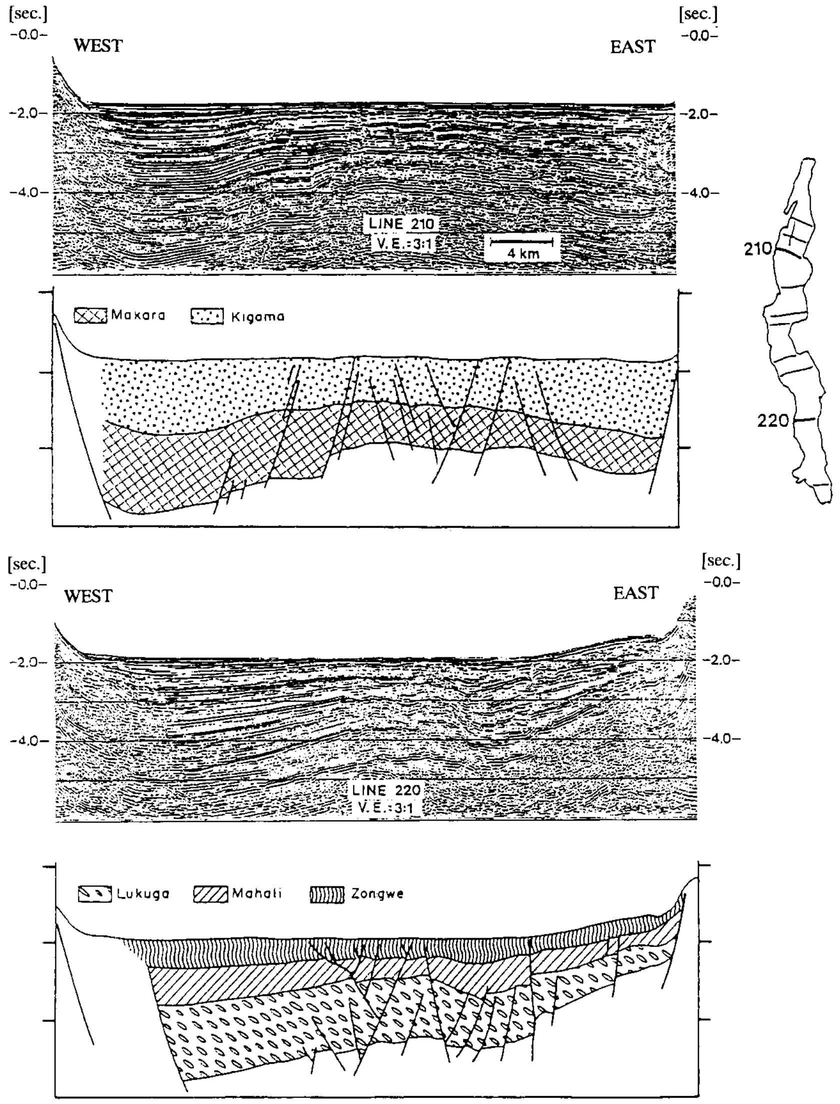

Fig. 7. Multichannel seismic profiles and interpreted cross-sections of line 210 and 220.

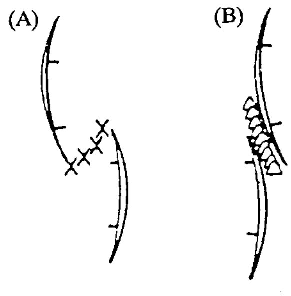

Fig. 8. Types of accommodation zone. Low-relief accommodation zone A) is marked by X, and high-relief accommodation zone B) is marked by Δ.

Tanganyika. It appears that the shape of the southern half-grabens is the product of Tertiary extension interacting with older structural fabric.

If it is assumed that all the half-grabens in the lake were generated by Tertiary rifting with one regional direction of extension, then that direction could not have been perpendicular to the entire rift because of the change in lake axis orientation (Fig. 9). Consequently, oblique extension must have produced the observed basin geometry in at least some portion of the lake. Although the actual extension direction is unknown, maximum subsidence along major border fault always occurs where the border faults trend in a

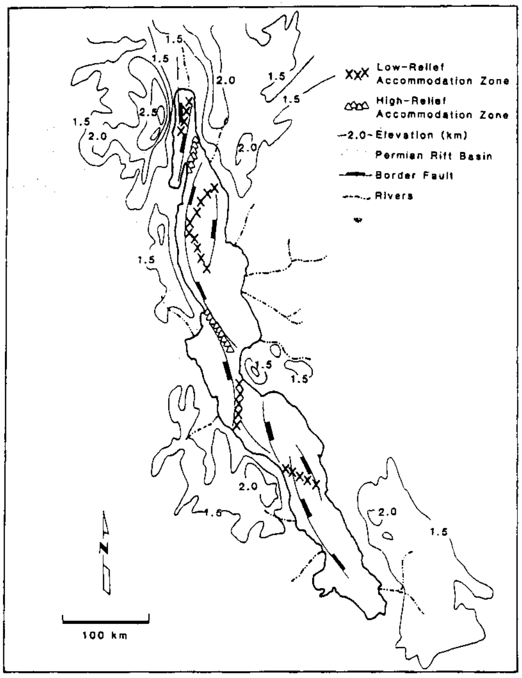

Fig. 9. Distribution of accommodation zones in Lake Tanganyika.

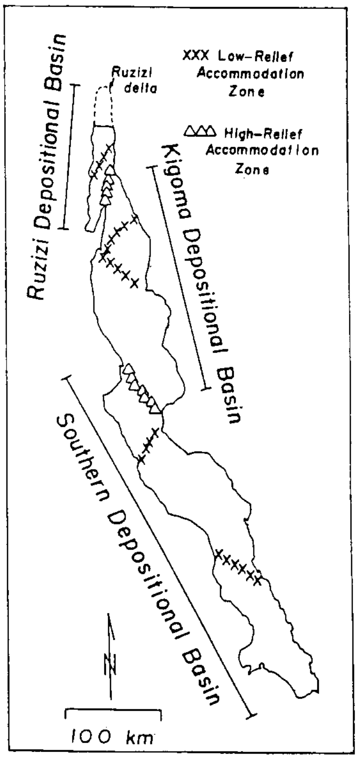

Fig. 10. Depositional basins in Lake Tanganyika created by two high-relief accommodation zones.

north-south direction. This suggests that the overall direction of extension for the Lake Tanganyika rift is approximately east-wast (Rosendahl, 1987).

Topography on the rift shoulder is related to internal structural geometry. Highest local elevations occur immediately adjacent to major border faults, and rift shoulders adjacent to the up-dip side of half-grabens are consistently at lower elevations (Fig. 9). This geometry affects stratigraphic development by influencing regional drainage patterns, and local environments of deposition

STRATIGRAPHIC DEVELOPMENT

Structural Controls on Deposition

Several aspects of the structural geometry of Lake Tanganyika strongly influence stratigraphic development. Probably the most important is the recognition of distinct half-grabens which produce discrete depositional basins within the lake. However, there is not a one-to-one relationship between half-grabens and depositional basins. Generally, a depositional basin consists of two or more adjacent half-grabens which are linked together by low-relief accommodation zones, and adjacent depositional basins are separated by high-relief accommodation zones. At the present time, there are two high-relief accommodation zones in Lake Tanganyika creating three separate depositional basins. These are the Ruzizi, the Kigoma, and the Southern depositional basins (Fig. 10). The high-relief accommodation zones seem to have been barriers to sediment dispersal through most of the rift's history because seismic reflections can not be correlated across these zones, and acoustic stratigraphy on either side of these zones are usually markedly different. Low-relief accommodation zones may periodically become topographic barriers, and sediment may onlap onto them (Fig. 11, line 259) if the local rate of sedimentation falls behind the rate of relative anticlinal development. However, unlike high-relief accommodation zones, the low-relief zones do not seem to have been long-term obstructions to sediment dispersal.

As mentioned above, rift shoulder topography controls regional drainage patterns and sediment access into the lake. The high shoulders adjacent to the master border fault systems usually deflect drainage away from the lake, whereas the ramped shoulders on the up-dip edge of half-grabens usually encourage drainage into the lake. These relations are seen in the present distribution of rivers relative to

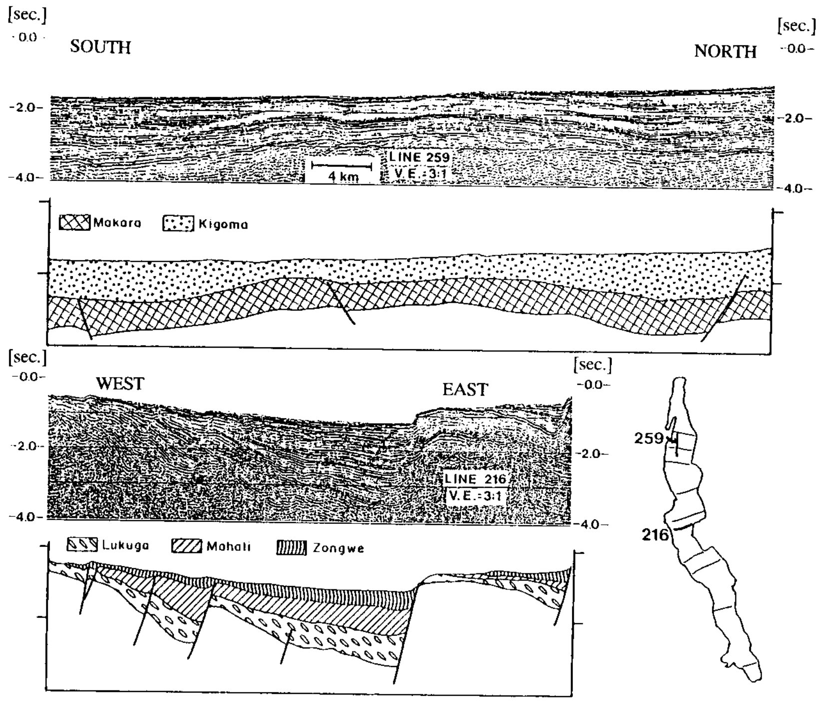

Fig. 11. Multichannel seismic profiles and interpreted cross-sections of line 259 and 216.

half-graben geometry (Fig. 9). Thus in modern Lake Tanganyika, sediment enters the rift mainly on the up-dip or shoaling sides of half-grabens. Because water depth typically mimics structural geometry, the sediment-input sides of half-grabens are usually the shallowest part of the lake. These areas must have been the sites of fluvial and deltaic sedimentation as well as other shallow-water, littoral environments. Deep-water shales and turbidites occur down-dip and may be restricted to the deep side of half-grabens. As much as 6,000 meters of sediment have been deposited in the deepest parts of the half-grabens.

The seismic data from Lake Tanganyika have been interpreted stratigraphically two depositional basins within the lake (Fig. 10). Each of these comprises more than one half-graben whose evolution and geometry control the distribution of seismic stratigraphic sequences. The structural style of each depositional basin is depicted in Fig. 3, and representative seismic lines for each basin are described below.

The Kigoma Depositional Basin

The Kigoma depositional basin is defined as the entire area between the two high-relief accommodation zones (Fig. 10). One major sequence boundary divides the sediments of the Kigoma basin into two seismic sequences. As used here, a seismic sequence is the seismic expression of a depositional sequence as defined by Mitchum *et al.* (1977). The lower unit rests on acoustic basement and is called the Makara sequence; the upper unit extends upwards from the sequence boundary to the lake floor and is called the Kigoma sequence. This sequence boundary is typically identified by truncation of Makara reflectors and onlap of Kigoma reflectors (e.g. Fig. 4, line 212). The base of the lower Makara sequence is defined by three or four high-amplitude and very continuous reflections which typically constitute acoustic basement. This set of reflections has been named the Nyanja event (Lorber, 1984). In most areas of the lake, the reflections lying directly above the Nyanja event onlap or downlap against this basement reflection, making the top of the Nyanja event a reliable seismic sequence boundary. The Nyanja event also defines acoustic basement in all other basins of Lake Tanganyika. The persistence of this basement reflection combined with the onlapping or downlapping configuration above, and its paleo-relief make it likely that the Nyanja event is a regional unconformity marking the onset of Tertiary rifting in this region of East Africa. The three or four cycle character of the event may be the acoustic signature of a thick weathered zone along the unconformity surface.

In the lower Makara sequence, wedges of transparent acoustic facies are common, especially along

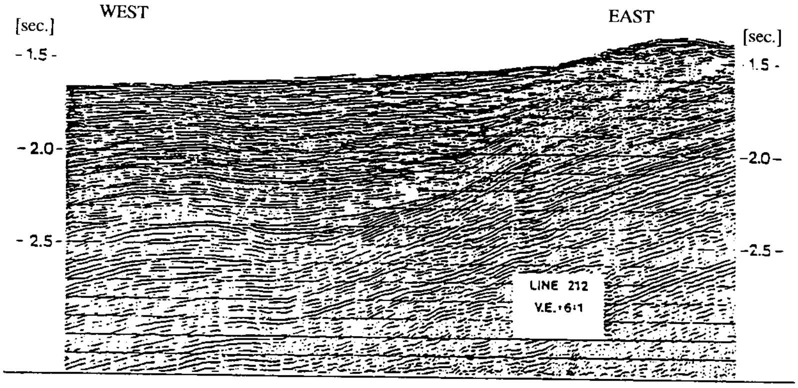

Fig. 12. A close-up of a portion of multichannel seismic profile of line 212.

the base of large faults (Fig. 5, east side of line 206). These transparent acoustic facies probably represent alluvial or sublacustrine fanglomerates. Just above the sequence boundary, within the lower Kigoma sequence, relatively low amplitude and discontinuous acoustic facies often occur. The transparency of these facies increases markedly over elevated areas, as shown on line 259 (Fig. 11). Fig. 12 shows a close up of a portion of line 212. This figure indicates that the transparent facies seems to grade landward into lower-continuity, variable-amplitude facies, and basin- ward into higher-continuity, high-amplitude facies. This type of seismic facies relationship is usually a response to sandy, terrestrial lithologic facies (Sangree, Widmier, 1977) such as fluvial, deltaic or shoreline sands. The entrance of these clastic sediments into the basin may be a response to a long-term change in climate or to a pulse of tectonic activity within the rift. Either one of these events, or both, could have increased the volume of clastic sedimentation in the Tanganyika rift at the time represented by these facies. It is probable that where onlap, truncation, and associated transparent facies all occur, the sequence boundary is a major erosional unconformity caused by a relatively low lake level which, in turn, was created by tectonic and/or clinatic events.

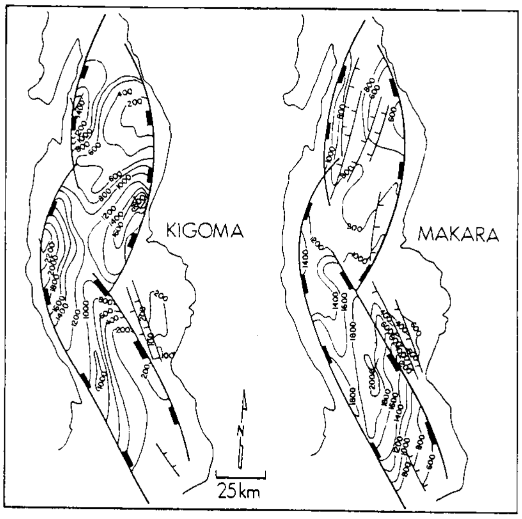

Fig. 13. Isopach map in two-way travel time for the Kigoma and Makara acoustic units.

Evidence for recent erosion can be seen on the eastern side of line 212 (Fig. 4) which was shot adjacent to the modern Malagarasi River. Here, channels up to 75 meters deep are incised into the older rift sediments. The deepest of these channels may be the ancient Malagarasi River channel which was cut during the last low-stand in lake level, estimated to have been 600 meters below its present level during the Late Pleistocene (Hecky, Degens, 1973). The oldest sequence, the Makara, has one major depocenter in the southeastern Kigoma Basin (Fig. 13). There is evidence for considerable erosion of this sequence in the southern part of the Kigoma Basin (Fig. 6, line 214). This erosion is probably responsible for unusual shape of this depocenter. The sequence seems to thicken toward the southeastern border fault, and some internal reflectors tend to diverge toward the west (Fig. 4, line 212). Apparently, the southeastern border fault was more active than the other fault systems in the Kigoma Basin during Makara time. Most subsidence took place along this border fault system, and depositional dip was probably in a southeastern direction.

The younger sequence, the Kigoma, has three major depocenters (Fig. 13). The depocenter which has formed in the southern part of the basin during this time has been controlled by the southwestern border fault system. Another thick depocenter has been forming along the northeastern border fault at about the same time. The northwestern border fault also has been active, and a third depocenter is found adjacent to it. Axial anticlines formed in the central area of the basin as the basement and overlying rift sediments were warped into low-relief accom- modation zones (Fig. 7, line 210; and Fig. 11, line 259). Depositional dip direction in the southeastern portion of the basin was altered, perhaps even reversed, as the southeastern border fault system became less active than the southwestern border fault. Certainly this tectonic change must have had profound effects on the drainage patterns of entering rivers, and sediment distribution within the Kigoma Basin.

The Kalemie Half-Graben

From the southern high-relief accommodation zone to the southern end of Lake Tanganyika, there are a complex series of half-graben units; one of them is the Kalemie half-graben (Fig. 3). The Kalemie half-graben dip east. Because this half-graben is not linked by high-relief accommodation zones, there are no basement ridges to act as barriers to sediment dispersal.

In the Kalemie half-graben all of the major faults dip west, and the strata dip east, forming several long, narrow fault blocks (Fig. 3). Seismic sequence boundaries are most evident along the upturned, western corners of these blocks. Here there are truncated reflections along the upper surfaces of the older sequences and onlapping or downlapping reflections along the lower surfaces of younger sequences. Two of these sequence boundaries have been identified, dividing the rift sediments into the three seismic sequences displayed on the interpretations of line 214 (Fig. 6) and 216 (Fig. 11). From oldest to youngest, these seismic sequences will be referred to as the Lukuga, Mahali, and Zongwe sequences.

In the Kalemie half-graben, depocenter position has always been controlled by western-dipping fault systems. During the earliest stage of basin evolution, represented by the Lukuga sequence, reflectors diverge into the down-thrown side of large normal faults, which indicates that this earlier stage of rift formation involved active faulting across the entire width of the half-graben as sediment accumulated. This can be seen best on lines 214 (Fig. 6). As the basin continued to develop, most of the fault activity took place along the eastern most border fault near the edge of the present lake margin, forming one or two relatively wide depocenters (Fig. 14).

CONCLUSION

Given the tectonic evolution, structural geometry,

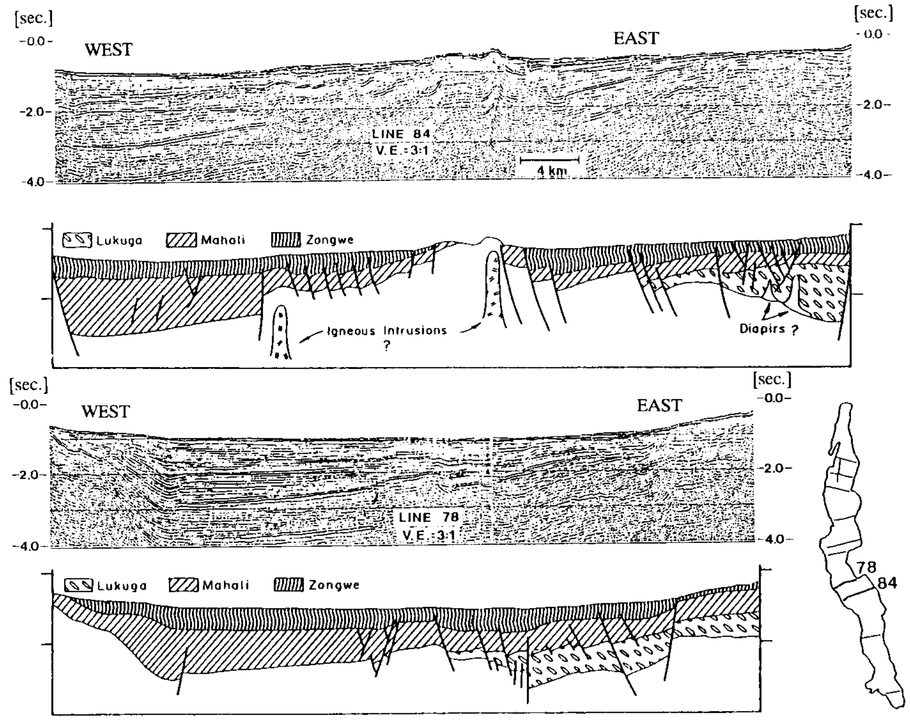

Fig. 14. Multichannel seismic profiles and interpreted cross-sections of line 84 and 78.

and stratigraphic development of the Lake Tanganyika rift, an important concern is the similarity of this rift to others. The Lake Tanganyika theme of rifting was probably characteristic of many continental rifts. Data from several extensional systems have increasingly recog- nized the asymmetric half-graben geometry (Gibbs, 1984; Ghignone, de Andrade, 1970). Also, the alternation of dip provinces along the strike of a rift, as manifest in alternating half-grabens, has been documented (Gulf of Suez: Moustafa, 1976; Rio Grande Rift: Baldridge *et al.*, 1984). Gravity data from the Rhinegraben (Sittler, 1969), structural and stratigraphic data from the Reconcavo Basin (Ghignone, de Andrade, 1970; Cohen, 1985), the Songliao Basin (Chen, 1980; Li *et al.*, 1982), and the Bohai Gulf (Desheng, 1980; Guangjia, 1980) are also consistent with the Tanganyika model of continental rifting.

The present study has benefited enormously from the excellent data quality from Lake Tanganyika and by the few complications to the general theme. Several conclusions can be drawn from this seismic reflection study. One of the most significant is the recognition that, although the rift is divided into discrete subbasins, there is not a direct correlation between structural and depositional subbasins. The fundamental structural units are half-grabens that alternate dip-direction along the rift axis. These are linked by accommodation zones that are areas of strike-slip faulting. The linking geometry of half-grabens has numerous variations, including one which produces apparent full-graben geometries via the juxtaposition of two half-grabens.

The structural and stratigraphic evolution of the rift has been dynamic, with numerous temporal changes in depocenter size and location. Stratigraphic development strongly reflects the structural history and geometry of the rift. Depositional basins are bounded by high-relief accommodation zones, and such basins generally span two or more adjacent half-graben units. Because high-relief accommodation zones appear to have been barriers to sediment dispersal throughout most of the rift's history, it would seem that the basic depositional architecture of the Tanganyika rift developed early. Low-relief accommodation zones act as modifiers to the basic architecture because such zones continue to develop throughout the history of a depositional basin. If development of these low-relief accommodation zones outpaces sedimentation, then low-relief accommodation zones may periodically become topographic or bathymetric highs, and sediment may onlap onto these anticlinal features. However, these low-relief accommodation zones are probably never barriers to sediment across the entire width of the rift. Transparent seismic facies associated with sequence boundaries are probably sandy terrestrial facies. Fluvial and deltaic sediments generally enter the rift from the up-dip side of half-grabens. Naturally, the proportion of fluvial and deltaic material to pelagic sediment will decrease toward the down-dip side. Turbidites and other mass-flow deposits are probably found throughout the deeper basins, and fanglomerates are probably found throughout the deeper basins, and fanglomerates are most likely concentrated along major border faults.

Data from other rift basins suggest that the tectonic, structural, and stratigraphic history of the Tanganyika rift represents a general theme of continental rift basin evolution. It seems that the observed differences among rift basins could be viewed as variations on this theme.

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아프리카 탕가니카호수의 구조 및 층서 진화 연구

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요 약 : 아프리카 동부의 탕가니카호수에서의 탄성파자료는 이 지역이 복잡한 판구조적, 구조적 및 층서적 역사를 가지고 있음을 보여주고 있다. 탕가니카호수의 열곡은 열곡의 주향을 따라 경사방향이 교대로 나타나는 반지구대(half-graben)로 구성되어 있으며 인접한 반지구대는 주향방향의 수용대 (收容帶; accommodation zone)로 분리되어 있다. 기반암이 비교적 높이 올라와 있는 수용대의 양쪽 면은 경계부 단층이 발달되어 있으며, 기복이 높은 수용대는 침강이 낮고 퇴적량이 적으며 기반암이 높이 올라와 있고 열곡발달 초기에 형성되었다. 또다른 수용대의 형태는 낮은 기복을 갖으며 상당량의 퇴적물을 갖고 단층이 발달된 배사구조로 구성되어 있다. 이런 지역은 열곡이 진행되어 가는 곳이다. 이러한 구조적 형태는 탕가니카 호수에서의 퇴적양상에 영향을 미치게 된다. 즉, 구조는 분지와 퇴적심(堆積心; depocenter)이 존재하는 곳에 영향을 미칠 뿐만 아니라 분지 내에서 공간적, 시간적으로 퇴적분포에 영향을 미치게 된다. 한편, 열곡 측면지형은 호수로 유입하는 유수 (drainage)의 형태나 퇴적물에 영향을 준다.