Normal vs. strike-slip faulting during rift development in East Africa: The Malawi rift

Uwe Ring
Institut für Geowissenschaften, Universität Mainz, Saarstrasse 21, D-6500 Mainz, Germany
Christian Betzler
Geologisches Institut, Universität Frankfurt, Senckenberganlage 32-34, D6000 Frankfurt am Main, Germany
Damian Delvaux
Musée Royal de l'Afrique Centrale, Leuvensesteenweg 13, B-3080 Tervuren, Belgium

ABSTRACT

Kinematic analysis of Neogene and Quaternary faults demonstrates that the direction of extension in the Malawi rift rotated from east-northeast to southeast. Rift development commenced with the formation of half-grabens bounded by northwest-, north-, and northeast-striking normal faults. Owing to slightly oblique rifting, the northwest-striking faults in the northernmost rift segment show a small dextral oblique-slip component, whereas north- and northeast-oriented faults in the central part of the rift display a sinistral oblique-slip component. This first event resulted in block faulting and basin subsidence, which is largely responsible for the present-day basin morphology of Lake Malawi. A major change in fault kinematics occurred because of rotation of the extension direction and permutation of the principal compressive and intermediate axes. The structural pattern inherited from the first rifting phase was no longer suitably oriented to accommodate extensional deformation, and strike-slip faulting assumed a major role. The strike-slip regime amplified uplift of basement ridges within the rift in regions of local transpression, but it also created alluvial basins because of local transtension. This new kinematic style is compatible with the recent seismicity. Older faults that show mainly the first deformational increment are restricted to the outermost parts of the rift. Toward the center, the faults depict an increase in strike-slip components of movement, suggesting deformation propagation toward the rift center, which results in a narrowing of the active rift environments with time.

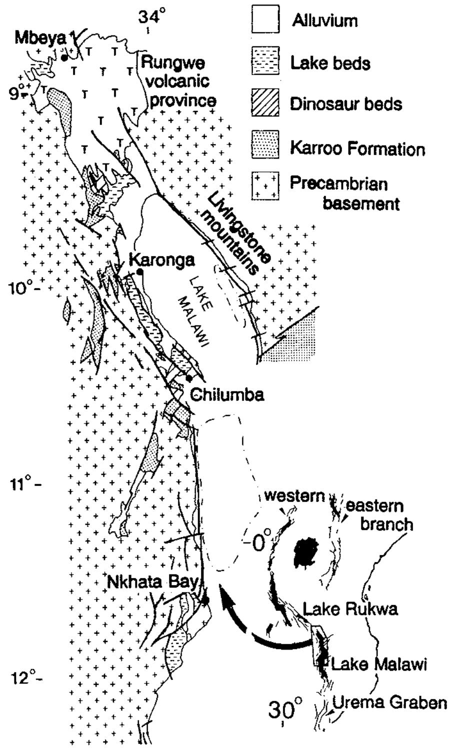

Figure 1. Generalized geologic map of northern Malawi rift showing main faults and lake depocenters (dashed lines) adjacent to border-fault segments. Index map shows position of Malawi rift within framework of East African rift.

INTRODUCTION

Continental rift zones provide impressive examples of the early stages of continental breakup by extension. Some rifts eventually mature into oceans. Most rifts, however, abort after a few kilometres of extension. Changes in the direction of extension have been recorded from various rifts and are the result of either permutations or rotations of principal kinematic axes (e.g., Illies and Greiner, 1978; Strecker and Bosworth, 1991). Previous investigations suggest that the direction of extension in the Malawi rift remained constant throughout rifting, either east-northeast (Ebinger et al., 1987, 1989) or, in an alternative view, southeast (Tiercelin et al., 1988; Wheeler and Karson, 1989). However, herein we report on the kinematics of superimposed faulting revealing a clockwise rotation of the extension direction, and we discuss implications of this rotation for the rift evolution.

GEOLOGIC FRAMEWORK

The Malawi rift belongs to the western branch of the East African rift system and extends more than 900 km from the Rungwe volcanic province in the north (southern Tanzania) to the Urema graben in the south (Mozambique) (Fig. 1). It consists of several individual asymmetric basins bordered by major faults on one side (border-fault segments) and en echelon step faults and flexures with minor vertical offsets on the opposite side. The discrete basins are linked through accommodation zones (e.g., Bosworth, 1985; Rosendahl, 1987). Basin subsidence, sediment accumulation, and rift-flank uplift are greatest in the northern basins and decreased southward (e.g., Ebinger et al., 1987), suggesting that the rift propagated in a zipperlike mode from north to south. Prerift anisotropies are thought to control the overall architecture of the Malawi rift (e.g., Versfelt and Rosendahl, 1989).

On the basis of radiometric dating of the alkalic Rungwe volcanic rocks, Ebinger et al. (1989) concluded that rifting began at ca. 8 Ma, the volcanism continuing to the present. The succession of the onshore lake sediments (i.e., Chiwondo and Chitimwe beds; e.g., Crossley, 1984) represents a large-scale transgressive-regressive tectono-sedimentary cycle. A major angular and erosional unconformity occurs between the Chiwondo and the overlying Chitimwe beds. The Chiwondo beds dip moderately (7°–15°) to the northeast (mean dip direction N53°E). Vertebrate fossils constrain the age of these sediments to between 4.5 and 1.6 Ma (F. Schrenk et al., unpublished). The Chitimwe beds are horizontally layered and their age is poorly constrained. The onshore lake sediments represent the westernmost tip of the wedge-shaped sedimentary rift fill visible in seismic reflection profiles (Scholz and Rosendahl, 1988; Scholz et al., 1990). The maximum thickness of the rift fill adjacent to the Livingstone border fault is suggested to be more than 4000 m (e.g., Specht and Rosendahl, 1989; Johnson and Ng'ang'a, 1990).

TECTONIC CHRONOLOGY AND KINEMATICS OF FAULTING

To evaluate the kinematics of the northern Malawi rift, major faults and fault intersections were structurally mapped with the aid of areal photographs and satellite images. Crosscutting relations of either faults and/or various distinct striations on one single fault plane supplied constraints on the relative faulting chronology. Most data stem from analyses in basement rocks, but additional structural data from the lake sediments allow determination of an absolute time sequence. Fault orientation, strike and dip of striations, and sense of relative displacement enabled the determination of principal strain axes ($X \geqslant Y \geqslant Z$) for each distinct fault family by means of a method outlined by G. W. Michel (unpublished). It became common during the past decade to relate fault-slip analysis to the state of stress or paleostress. However, the correlation between stress and strain is in general noncoaxial (e.g., Wittke, 1984); therefore, the investigation of faults and movements on them leads strictly to displacement vs. strain relations rather than to the applied stress.

In the Karonga-Chilumba area, the first faulting increment is clearly evidenced only at the westernmost margin of the rift (Fig. 2). Normal movements (principal compression axis, Z, vertical) occurred on northwest-striking to north-northwest–striking, slightly curved faults during east-northeast–oriented extension (X axis or stretching vector). Transfer faults developed parallel to the initial opening direction. Normal faulting along major basin-bounding faults is locally accompanied by gravitational collapse of the footwall, creating listric faults with down-dip slickenside striations. On a mesoscale, these gravity-induced structures match in style and orientation the tectonically induced rift-forming faults. Toward the rift center, early normal faults are hard to identify and their orientation is more scattered. The second faulting increment is largely dominated by strike-slip movements along the older normal faults and generated dextral strike-slip and dextral oblique-slip faulting. Several synthetic Riedel or R shears and only a few antithetic, or R′, shears formed. The principal extension direction rotated slightly to an eastward direction, the Z axis approaching a horizontal north-south orientation. Continuing strike-slip deformation led to clockwise rotation of the stretching vector to an east-southeast to southeast direction. The structural pattern inherited from the first rifting phase was no longer suitably oriented to accommodate deformation, and new north-northwest–striking to north-striking faults formed. Preexisting faults were partly reactivated as oblique-reverse or oblique-normal faults. During strike-slip deformation, especially during the last increment, the tectonic regime yielded a combination of strike-slip, oblique-slip, and dip-slip faults; thus, the magnitudes of the principal compression and the intermediate (Y) axes are almost identical, and so their orientations are not tightly constrained.

The Rungwe area of southern Tanzania (Fig. 3A) shows a similar faulting sequence. Along the Livingstone border-fault segment, all three increments occurred; however, a shift in faulting toward the rift center, as observed in the Karonga-Chilumba area, was not recognized.

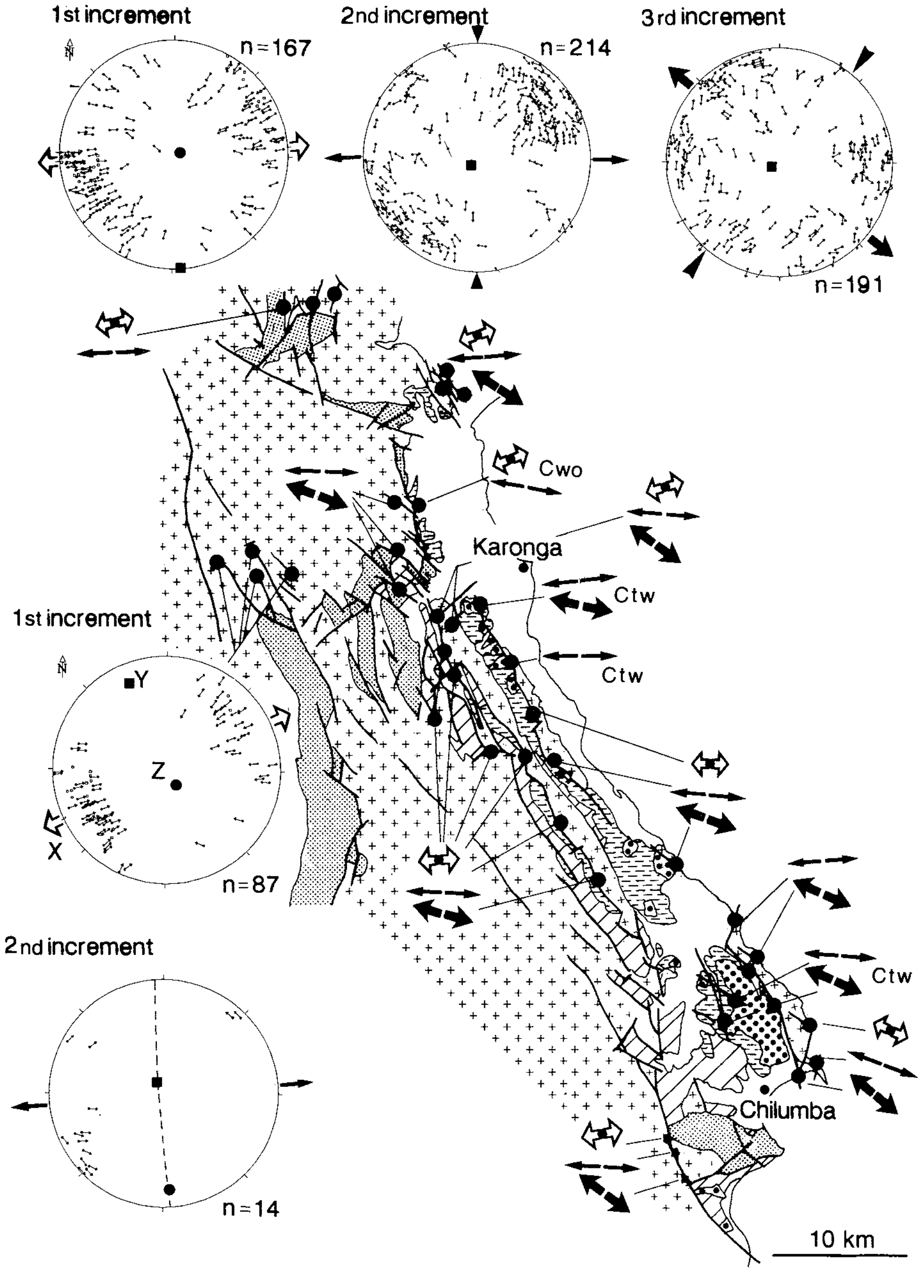

Figure 2. Lithology and structure of Karonga-Chilumba area; big dots mark locations where fault-slip analyses were done. Lower-left plots show data from westernmost rift margin; plots at top illustrate data from all other areas. Plots are synoptic and illustrate data from different outcrops. Plots show poles to faults with trace of striae (method of Hoeppener, 1955); calculated directions represented by diverging arrows (extension, *X*), squares (*Y*), and circles or converging arrow heads (compression, *Z*). First increment led to faulting under east-northeast–oriented extension; fault striae are best preserved at western rift margin. Second increment shows dominantly strike-slip faulting, whereas third increment shows strike-slip, normal, and reverse faulting that prevails in the southeast where new strike-slip, normal, and reverse faults formed during southeast extension. In map, arrows depict principal extension axes (axes were determined for each single outcrop; vector mean of single determinations is shown); data from Chiwondo (Cwo, dashed pattern in map) and Chitimwe beds (Ctw, heavy dotted pattern in map) are indicated; note that first increment is not indicated in Chitimwe sedimentary strata. Other patterns as in Figure 1.

Early-formed normal faults locally rotated in zones of enhanced deformation into a shallower attitude (i.e., around a horizontal axis out of a suitable position) and were subsequently cut by a new generation of normal faults. In general, the early normal faults at the eastern rift margin show a broader scatter than at the westernmost margin; thus, the calculated extension directions are less well defined.

In the Nkhata Bay region of central Malawi (Fig. 3B), the first increment produced mainly normal faulting, whereas along the northeast-trending rift segment south of Nkhata Bay, sinistral oblique-slip and normal faults formed under prevailing east-northeast–directed extension. The later phase led to dextral oblique-slip and dip-slip faulting due to southeast-oriented extension. No reverse or oblique-reverse faults formed in this part of the rift.

Tension gashes have been observed in all rock types. They are almost vertical and indicate extension directed either east-northeast (N60°–70°E) or northwest (N130°–140°E). In the Chitimwe beds, only the latter direction was observed.

DISCUSSION

Two general stages of rift formation can be distinguished: an early phase of normal faulting followed by a strike-slip–dominated system (Fig. 4). Normal faulting during east-northeast extension led to the opening of the Malawi rift by block faulting and basin subsidence and resulted in the formation of half-grabens. Normal faulting caused tilting of the Chiwondo beds in the Karonga-Chilumba area around a horizontal axis to approximately N75°E (stretching vector), but owing to oblique rifting (extension not perpendicular to rift boundaries; e.g., Tron and Bruhn, 1991) in this rift segment, some back rotation around a vertical axis probably occurred (i.e., bed dip was likely N65°–70°E). The onset of volcanic activity and tilting of the Chiwondo beds constrain this phase to a period between 8 and <1.6 Ma.

The change to dominantly strike-slip faulting is interpreted to be due to rotation of the X axes and incipient permutation of the Z and Y axes. Strike-slip deformation led to rotation of the sedimentary strata around a vertical axis and therefore did not occur earlier than 1.6 Ma. The present-day mean dip direction of the Chiwondo beds (N53°E) indicates approximately 12°–17° sinistral (i.e., backward) rotation if N65°–70°E is assumed to be the original dip direction. The principal strain axes of this tectonic regime were not tightly constrained. However, because of (1) the generally horizontal position of the compression axis and (2) the clockwise rotation of the extension axis, the early-formed normal faults became susceptible to reverse or oblique-reverse movements. During strike-slip deformation, especially during the last increment, strike-sliip movement together with normal and reverse-slip movements led to localized areas of transtension and transpression, respectively.

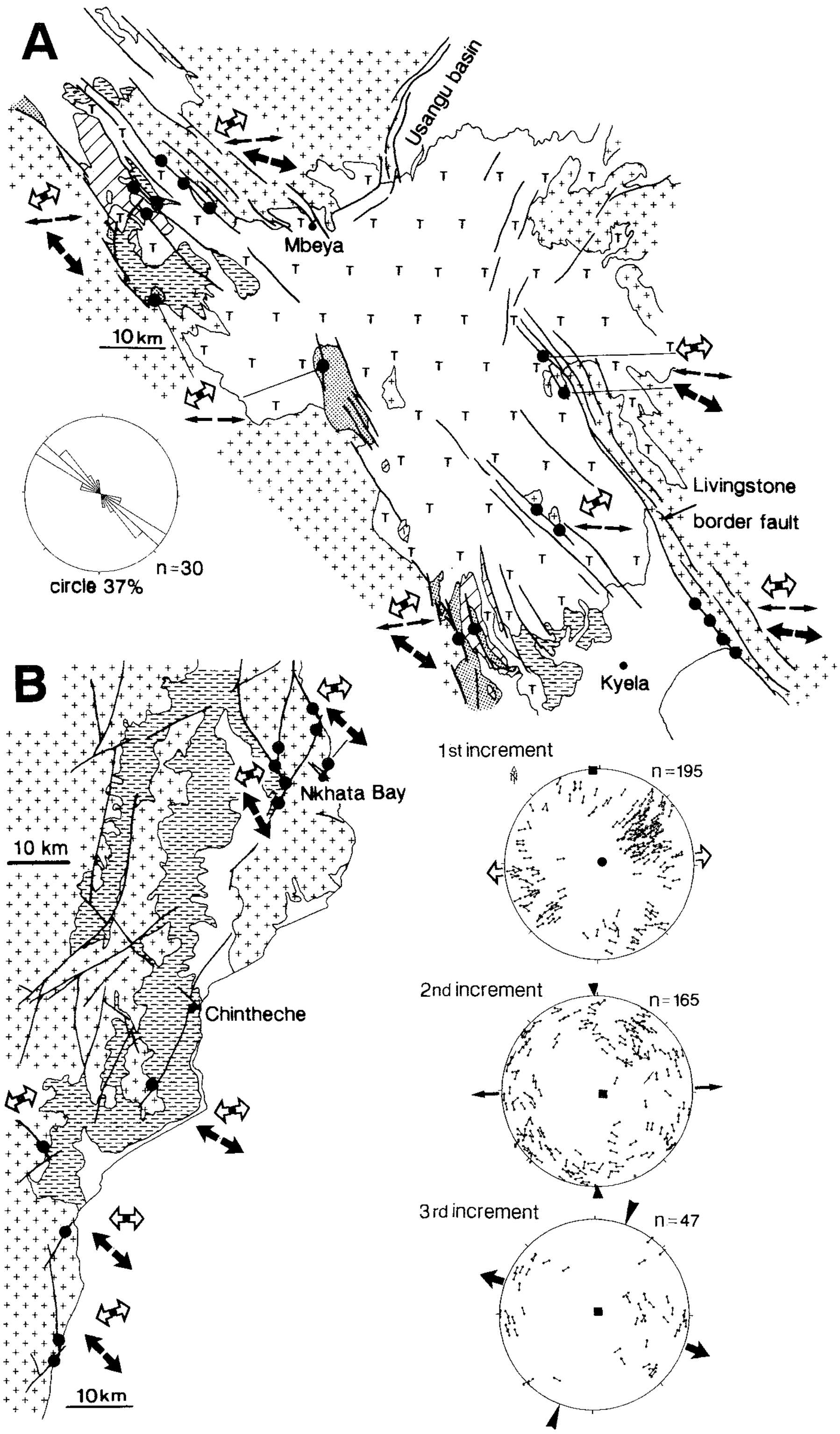

Figure 3. Structural and lithological sketch maps of (A) Rungwe and (B) Nkhata Bay-Chintheche areas; symbols and patterns as in Figures 1 and 2. Faulting increments depict essentially same characteristics as in Figure 2; owing to poor outcrops south of Nkhata Bay, distinction of three faulting increments was not possible. Lower right diagrams show data from Livingstone border fault. Rose diagram illustrates extension directions of third increment summarized from all data, which are in accord with recent seismicity (e.g., Shudofsky, 1985).

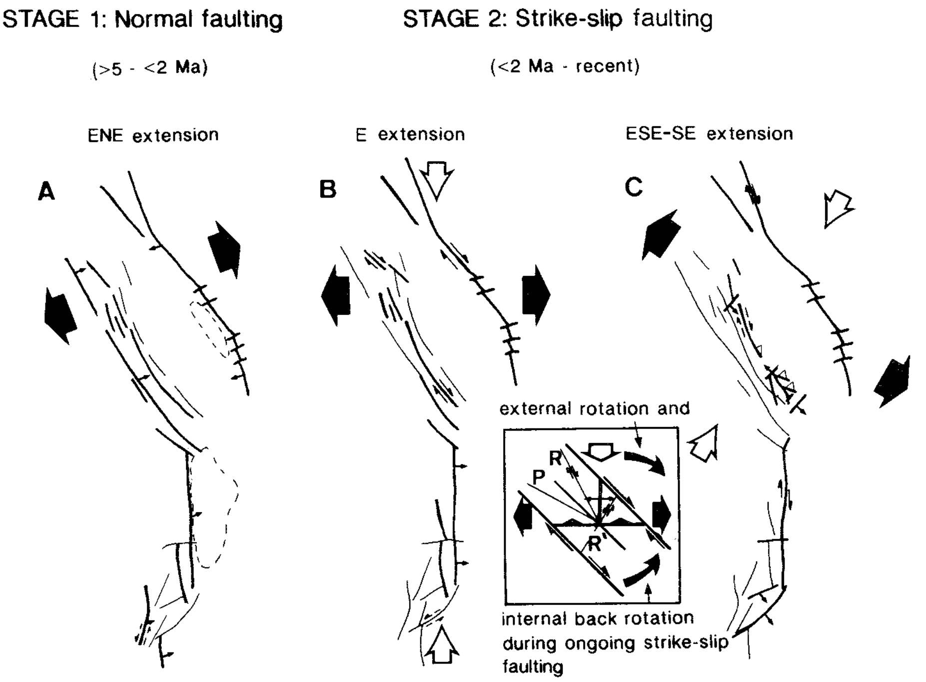

Figure 4. Simplified model for evolution of Malawi rift. A: Initial normal faulting produced asymmetric rift basins; dashed enclosures correspond to important lake depocenters. Mean fault trend in studied areas (N5°W) is not normal to early extension direction (N75°E). According to somewhat oblique rifting, faults depict slightly dextral oblique-slip components in north and sinistral oblique-slip components in central part of Malawi rift. Different trends of individual rift basins and fact that faults formed not perpendicular to stretching vector are possibly related to basement anisotropies. B: Switch to predominant strike-slip faulting; northwest- and also northeast-striking faults show strike-slip movement; other faults depict dip- or oblique-slip movement corresponding to position relative to principal axes. C: Rotation of principal axis because of continuing strike-slip (see also inset); reverse faulting became more pronounced.

Transtension created approximately northeast-oriented sedimentary basins. Transpression may be responsible for localized uplift of intrarift basement ridges along reverse and oblique-reverse faults and may also have contributed to rift-flank uplift during the most recent phases of rift development.

Our outline of the rifting evolution stems mainly from our analysis in the Karonga-Chilumba area, i.e., from the shoaling side of the rift. We think that the incremental steps of a tectonically active rift are best studied at this side, where lake sediments are exposed and en echelon step faults may reflect the successive faulting history. Border-fault segments, on the other hand, may accumulate large finite strains, reflecting the entire deformation history of the rift. Because of later rotations, the kinematics of early-faulting increments are more difficult to unravel.

Kinematic data from the East African rift are scarce; however, our data fit the rotation of the extension direction as observed by Strecker et al. (1990) in the central Kenya rift. Strecker et al. reported a switch from dominantly east-directed extension during the Pliocene to southeast-oriented extension at about 0.4 Ma.

In the Rungwe area, some major faults are marked by an alignment of eruptive volcanic centers (Ebinger et al., 1989), suggesting planar faults. The relatively great subsidence (~6.4 km; Wheeler and Karson, 1989) compared to the small amount of extension (~3.5 km; Specht and Rosendahl, 1989) suggests strong vertical movements during much of the rifting history, which were probably caused by coaxial extension with a low shear component along the faults. Nevertheless, there seems to have been a major late Quaternary change in the kinematic framework of East Africa (see also Strecker et al., 1990; Bosworth et al., 1992). In the Malawi rift, the rotation of the stretching vector resulted in a higher obliquity of rifting and therefore in a narrowing of the deformation zone (Tron and Bruhn, 1991), which may eventually lead to abortion of the rifting process.

ACKNOWLEDGMENTS

This study is part of the Hominid Corridor Research Project (HCRP), which is funded by the Deutsche Forschungsgemeinschaft. We thank the governments of Malawi and Tanzania for permission to conduct this research. G. Michel, T. Bromage, F. Schrenk, C. Ebinger, M. Strecker, O. Oncken, W. Wheeler, H. Mullins, and B. Rosendahl provided valuable suggestions.

REFERENCES CITED

Bosworth, W., 1985, Geometry of propagating continental rifts: Nature, v. 316, p. 33–37.

Bosworth, W., Strecker, M.R., and Blisniuk, P.M., 1992, Integration of East African paleo and present-day stress data: Implications for continental stress field dynamics: Journal of Geophysical Research (in press).

Crossley, R., 1984, Controls on sedimentation in the Malawi Rift Valley, central Africa: Sedimentary Geology, v. 40, p. 33–40.

Ebinger, C.J., Rosendahl, B.R., and Reynolds, D., 1987, Tectonic model of the Malawi Rift, Africa: Tectonophysics, v. 141, p. 215–235.

Ebinger, C.J., Deino, A.L., Drake, R.E., and Tesha, A.L., 1989, Chronology of volcanism and rift basin propagation: Rungwe volcanic province, East Africa: Journal of Geophysical Research, v. 94, p. 15785–15803.

Johnson, T.C., and Ng'ang'a P., 1990, Reflections on a rift lake, *in* Katz, B.J., ed., Lacustrine basin exploration: American Association of Petroleum Geologists Memoir 50, p. 113–135.

Hoeppener, R., 1955, Tektonik im Schiefergebirge: Geologische Rundschau, v. 44, p. 26–58.

Illies, J.H., and Greiner, G., 1978, The Rhinegraben and the Alpine system: Geological Society of America Bulletin, v. 89, p. 770–782.

Rosendahl, B.R., 1987, Architecture of continental rifts with special reference to East Africa: Annual Review of Earth and Planetary Sciences, v. 15, p. 445–503.

Scholz, C.A., and Rosendahl, B.R., 1988, Low lake stands in Lakes Malawi and Tanganyika, East Africa, delineated with multifold seismic data: Science, v. 240, p. 1645–1648.

Scholz, C.A., Rosendahl, B.R., and Scott, D.L., 1990, Development of coarse-grained facies in lacustrine rift basins: Examples from East Africa: Geology, v. 18, p. 140–144.

Shudofsky, G., 1985, Source mechanisms and focal depths of East African earthquakes using Raleigh wave inversion and body-wave modelling: Royal Astronomical Society Geophysical Journal, v. 83, p. 563–614.

Specht, T.S., and Rosendahl, B.R., 1989, Architecture of the Malawi rift, East Africa: Journal of African Earth Sciences, v. 8, p. 355–382.

Strecker, M.R., and Bosworth, W., 1991, Quaternary stress-field change in the Gregory Rift, Kenya: Eos (Transactions, American Geophysical Union), v. 72, p. 17, 21–22.

Strecker, M.R., Blisniuk, P.M., and Eisbacher, G.H., 1990, Rotation of extension direction in the central Kenya rift: Geology, v. 18, p. 299–302.

Tiercelin, J.J., Chorowicz, J., Bellon, H., Richert, J.P., Mwanbene, J.J., and Walgenwitz, F., 1988, East African rift system: Offset, age, and tectonic significance of the Tanganyika-Rukwa-Malawi intercontinental transcurrent fault zone: Tectonophysics, v. 148, p. 241–252.

Tron, V., and Bruhn, J.P., 1991, Experiments on oblique rifting in brittle-ductile systems: Tectonophysics, v. 188, p. 71–84.

Versfelt, J., and Rosendahl, B.R., 1989, Relationships between pre-rift structure and rift architecture in Lakes Tanganyika and Malawi, East Africa: Nature, v. 337, p. 354–357.

Wheeler, W.H., and Karson, J.A., 1989, Structure and kinematics of the Livingstone Mountains border fault zone, Nyasa (Malawi) Rift, southwestern Tanzania: Journal of African Earth Sciences, v. 8, p. 393–413.

Wittke, W., 1984, Felsmechanik: Heidelberg, Springer-Verlag, 1050 p.

Manuscript received March 24, 1992
Revised manuscript received July 10, 1992
Manuscript accepted July 22, 1992