Tectonic Model of the Malaŵi Rift, Africa

by

Cynthia Joan Ebinger

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Submitted to the Department of
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Signature of Author: ___
Department of Earth, Atmospheric,
and Planetary Sciences
May, 1986

Certified by: ___
Leigh Royden
Thesis Supervisor

Certified by: ___
Graham Michael Purdy
Thesis Supervisor

Accepted by: ___
William Brace, Chairman
Graduate Student Committee

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ABSTRACT

In the active Malaŵi rift (Africa), uplifted segments of the border fault system flank basins with different acoustic stratigraphies, sediment thicknesses, and styles of faulting. Regionally, curvilinear border fault segments bound sigmoidal-shaped basins and are linked along the length of the rift in accommodation or transfer fault zones. Transfer fault zones that trend oblique to the approximately N-S trend of the rift system and border fault segments accommodate differential movements between extensional segments. Transfer faults occur within the rift valley bounded by border faults, suggesting little thinning occurs beneath the elevated rift flanks. Cross-sectional morphologies and fault patterns within the rift basins depend on the geometrical arrangement of border fault segments, and these patterns are similar to those observed in the Tanganyika rift.

Border fault segments locally may reactivate or have an orientation sub-parallel to Proterozoic-Mesozoic structures, but the 100 km border fault segmentation and alternating asymmetries of rift basins show little correlation with ancient faults and geologic contacts. The central parts of border fault segments in both the Malaŵi and Tanganyika rifts, where maximum vertical displacements have been observed, are separated by 50-90 km along the length of the Malaŵi and Tanganyika rifts. The uniform separation of the central parts of border fault segments in both the Malaŵi and Tanganyika rifts, despite differences in age and geologic setting suggest that stress concentrations with an average spatial wavelength of 70 km occur along the length of the Tanganyika and Malaŵi rifts.

Thesis Supervisors: Dr. Leigh Royden
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Dr. Graham Michael Purdy
Woods Hole Oceanographic Institution

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Without the ideas of Dan Livingstone and Bruce Rosendahl, beautiful Malaŵi would never have been visited; without the optimism and efforts of Capt. Barrett, Ross Dunseath, Michael Crow, Jeff Nelson, Marcus Patterson, Francis Spy-Anderson and the crew of the tiny Orion, these seismic data would never have been collected, and my pangolin scale never earned. In the near future, I hope to say "Asanti sana" to Jim Broda, G.M. Purdy, Deb Scott, and Beecher Wooding (my partners in limbo).

And the priestess spoke again and said,
Speak to us of Reason and Passion.

Your reason and your passion are the rudder and sails
of your seafaring soul.
If either your sails or your rudder be broken, you can but
toss and drift, or else be held at standstill in mid-seas.
For reason, ruling alone, is a force confining...
...you, too, should rest in reason and move in passion.

Kahlil Gibran, in The Prophet

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Structural Evolution of Lake Malaŵi, Africa

C. J. Ebinger*, M. J. Crow', B. R. Rosendahl$^+$, D. A. Livingstone$^+$,
and J. LeFournier#

*Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543,
USA

'Institute of Geological Sciences, Keyworth, Nottingham NG12 5GG, UK

+Duke University, Durham, North Carolina 27708, USA

#Societe Nationale Elf Aquitaine (Production), Boussens, France

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Over 2000 km of seismic reflection profiles have been collected in Lake Malaŵi (Nyasa), the southernmost of the East African Rift Lakes. These studies reveal a severely faulted lakefloor bounded by rift structures of Pliocene or greater age. Faults that penetrate the uppermost sedimentary units and numerous earthquakes[1] attest to ongoing activity in the rift. Interbasinal differences in fault spacing, orientation, and sedimentary thicknesses have led to a subdivision of Lake Malaŵi into four discrete structural provinces. These provinces only now are linked by faults attributed to the most recent episodes of extension. An evolutionary sequence of 1) initial block faulting and subsidence, 2) fragmentation of fault blocks, 3) uplift, and 4) renewed subsidence and rotation of fault blocks is proposed for the central part of the Malaŵi Rift.

Single-channel reflection surveys were conducted as part of a program to evaluate sites for a proposed deep-drilling project (CEGAL) in the East African Rift Lakes[2]. Profiles were obtained using an airgun sound source (40 cu. in.) occasionally supplemented by an 800 J sparker, and radar navigation provided the principal means of trackline control. A single 13 meter-long piston core was collected from the southern part of the lake (Figure 1).

With a length of 560 km and an average width of 50 km, Lake Malawi fills the central valley of the Malaŵi Rift (Figure 1). The lakefloor reaches a maximum depth of 700 m, or 225 m below sealevel[3]. Structural patterns[4] and geophysical data[5] indicate the Malaŵi Rift is tectonically connected to the western branch of the East African Rift system. Agreement on the actual age of initiation of the Malaŵi Rift has been hampered by the paucity of reliable field data and rock dating. Earlier researchers believed rifting commenced in the Jurassic-Cretaceous[6,7], but recent workers have suggested a much younger Pliocene age[4]. Faunas from the earliest known lacustrine sediments exposed onshore, the Chiwondo beds, have been dated at 2.5 to 5 My[8] and are separated from the overlying Chitimwe beds by an erosional event of unknown duration[9].

The surface geology to the west of Lake Malaŵi has been reported[9], but little information is available as to the age of faulting on the eastern shores (Tanzania and Mozambique).The results of a recent research program along the Tanzanian shores of Lake Malaŵi indicate the large vertical offset along the Livingstone Fault (Figure 1) is accompanied by an even greater amount of horizontal displacement (J. LeFournier, pers. comm.). Prior to our seismic survey knowledge of the lakefloor had been derived from a reconnaissance heat flow survey[11],a few echograms from the southwest arm of the lake[2] and a theoretical study of lakebed topography[12]. Sediment distribution was poorly known, but sand, mud, diatomite, and iron precipitates were found in the uppermost layers[13].

Set within the roughly north-south boundary fault system shown in Figure 1, the Malaŵi Rift transects Precambrian metamorphic basement and northeast-trending Mesozoic (Karroo) fault troughs. Some reactivation of pre-existing zones of weakness has been described onshore[4], and our seismic records show that submerged segments of the Maniamba and Ruhuhu Karroo faults troughs have been reactivated. The segmented character of the boundary fault system and inter-basinal differences in seismic stratigraphy lead to a division of the rift into four discrete structural provinces. Each province has a distinct fault pattern, and few faults extend between provinces; therefore, principal stress orientations are inferred to shift at province boundaries (Fig. 1). The provinces are typically 60 km long and 50 km wide, with the cross-sectional forms of half-graben. The main graben are composed of many closely spaced, usually tilted, fault blocks. Faults penetrate to all levels of the sedimentary column and diapiric features occur along some faults (Fig ures 2, 3).

The four provinces (Figure 1) reflect different stages of rift evolution, with the youngest, the Monkey Bay Province, showing the least amount of subsidence and fragmentation of major fault blocks (Figure 1). Maximum subsidence has occurred along the Western Boundary Fault (WBF) in the Nkhata Province where sediment thicknesses are also the greatest. A structural interpretation of the southern Nkhata Province is shown in the block diagram of Figure 2. Up to 2.0 km of subsidence is observed in the seismic records, but the actual amount could be much greater as basement was often obscured by the bottom multiple (Figure 3). Steeply dipping synthetic and antithetic normal faults trend roughly north-south within this province. Shallow earthquakes of magnitude three or greater correlate well with mapped structures and appear to be related to movements along the WBF and a mid-lake basement high (Figure 2).

In the southern part of the Nkhata Province, many northeast-trending faults (Figure 2) with little or no vertical offset are observed. These are interpreted as strike-slip faults that link this part of the Nkhata Province to the Nkhota-kota Province near the bend in the lake. A zone of transcurrent movement mapped onshore in this area[14] supports a strike-slip interpretation. In Lake Malaŵi the propensity toward half-graben morphologies could be related to oblique extension across the lake or between individual segments, as basin asymmetry alternates between provinces. Where rift segments are offset along strike this oblique extension would introduce a strong component of horizontal shear into the regional tensional regime. A similar alternating pattern of basinal asymmetry and transcurrent faults has been observed in the Rio Grande Rift[15].

Diapiric features observed along some faults in this area (Figures 2 and 3) could be related to the period of uplift which created or enhanced a mid-lake high. Although no rift-related igneous activity has been described onshore in the Nkhata region, the Rungwe volcanic zone to the north[16] (Figure 1) has been active since the Pliocene. These diapirs could be Rungwe-related igneous intrusive bodies or the lakebed equivalent of hydrothermal springs that occur along the WBF (Figure 1).

Many of the previously described features and relations are observed in a seismic line across the southern part of the Nkhata Province near the kink of Lake Malaŵi (Figure 3). The nearly cross-sectional seismic section shown in Figure 3 serves as the basis for the evolutionary sequence depicted in Figure 4. In order to remove non-diastrophic effects from the lakebottom morphology, reconstructions were made to acoustic horizons that are presumed to be time-stratigraphic. Information from nearby seismic lines also was used in the reconstructions. The Western Boundary Fault serves as a fixed point of reference for all four stages to illustrate the relative amount of extension that has occurred along this transect.

Little is known of the pre-rift terrains of central Africa. Therefore, Stage 1 depicts depositional pulses in an already faulted basin (Horizon A). Reconstruction to the top of acoustic (presumably crystalline) basement indicates the graben developed on the western margin of a broad dome. The north-south elongate rift apparently interrupted a west-to-east drainage pattern, capturing detritus derived predominantly from the west. The discontinuous, fuzzy reflectors of the lowermost acoustic unit are interpreted as the earliest Malawi Rift sediments, probably sands shed from the uplifted rift flanks. These sediments could be the equivalent of the shallow lake and alluvial plain deposits of the exposed Chiwondo Beds[9,10]. The wedge-shaped geometry of this basal unit suggests that a few faults in the central valley were active during the initial infill stages.

The period between Stages 1 and 2 was a period of extension and rapid subsidence as rift-flank drainage patterns became more extensive. At the time corresponding to Stage 2, the boundary faults were well-established and the rift had achieved most of its present width. Subsidence along the western fault proceeded much more rapidly than its eastern counterpart, and this asymmetry was enhanced by clastic input largely from the west. The parallel-banded reflectors in this middle unit are indicative of deep-water deposition of muds (via turbidity currents?) and biogenic oozes, with lake conditions presumed to be similar to those prevailing today. The geometry of acoustic laminations shows deposition on an uneven lakefloor concomitant with rotation of fault blocks.

Stage 3 is a reconstruction to the top of a strongly reflective, nearly horizontal layer (Horizon C) that appears to truncate the uplifted corners of rotated fault blocks. Deposition on continuously tilting fault blocks can account for only part of the reflector inclinations at this level, hence an erosional unconformity is proposed. Further evidence for a period of relative uplift is seen in the central lake area where a structural basement high developed (Figure 2). The intertonguing bed pattern in the adjacent central graben indicates sediments derived not only from the west but from a shallow or subaerially exposed mid-lake high. An apparently short-lived period of uplift in segments of Lake Malaŵi may be analogous to the mid-Jurassic doming episode observed in the central North Sea area[17], and to doming in the central basin of Lake Tanganyika[2]. Two major erosional events described for central Africa[18] could be related to drier periods and lowstands of the lake, but too little is known of the timing, duration, or extent of these events in the region surrounding Lake Malaŵi to make any well-constrained correlations at this time.

Stage 4 is an interpretation of the present-day structural and stratigraphic relations in the Nkhata Basin of Lake Malaŵi. Extension, rotation and continued fragmentation of fault blocks dominated the latest rift episode. Substantial movements along the border fault system led to general subsidence, while the lake refilled to its present level. The unconformity surface in the Nkhata Province was overlain by a 60-meter thick, acoustically "transparent" unit. Core studies of the upper 13 m show this to be a diatomite with minor clays and organic debris. In the extensional periods between stages 1 and 2 the border faults became more diffuse. The more rapid susidence between stages 3 and 4 was largely restricted to a 20-km wide central graben and was achieved by vertical and rotational movements along a few major faults. A similar narrowing of the zone of maximum subsidence also has been observed in the S. Kenya Rift[19].

An extrapolation of the chronologic history of the Nkhata Province to the remaining lake provinces indicates Lake Malawi has grown through the coalescence of structural basins during successive episodes of regional extension, uplift, and subsidence. Half-graben morphologies and fault patterns with strike-slip geometries (northeast trending faults) indicate the Malaŵi Rift is opening oblique to the axis of the rift (N-S). This is most apparent in the region surrounding the bend in the lake, which could evolve into a transform zone if the Malawi Rift becomes a true spreading system.

The areal dimensions of the four structural provinces (60 km by 50 km) are remarkably similar within Lake Malaŵi, the East African Rift System, and many other continental rifts. Fault patterns within the rift are influenced by pre-existing structural grains, but the dimensions of basins in the Malaŵi Rift remain fairly constant. Rosendahl and Livingstone[2] have suggested that the recurrence of these dimensions reflects a fundamental response of the lithosphere to the process of rifting that is only secondarily affected by pre-existing structural grains. Further studies in the rift lakes of East Africa, where it may be possible to observe continental separation in its juvenile stages, are needed to define the vertical and horizontal extent of basement structures within the extensional basins, and to relate the observed repeatability of dimensions to crustal, lithospheric, or asthenospheric properties.

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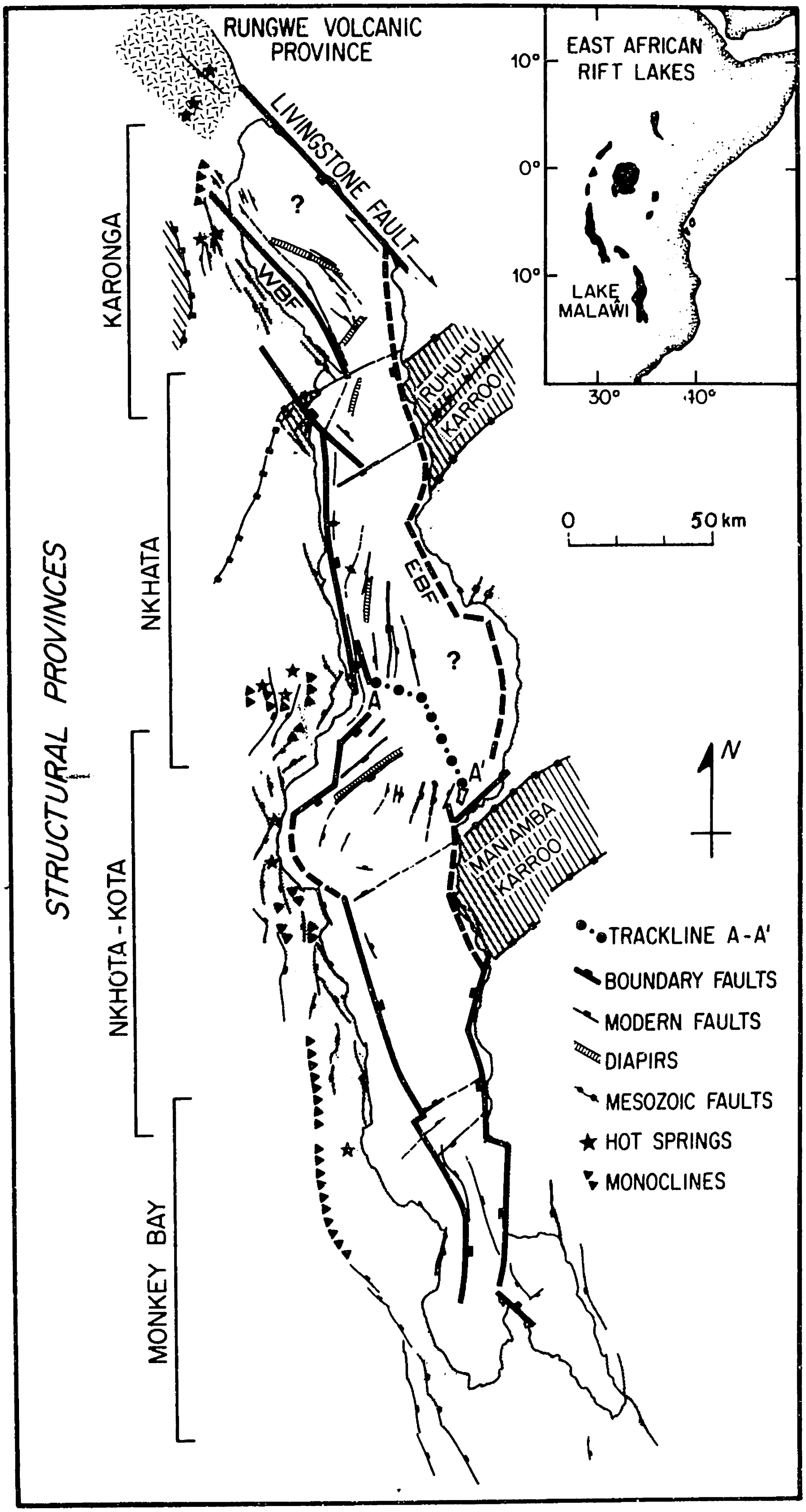
RUNGWE VOLCANIC PROVINCE
LIVINGSTONE FAULT
?
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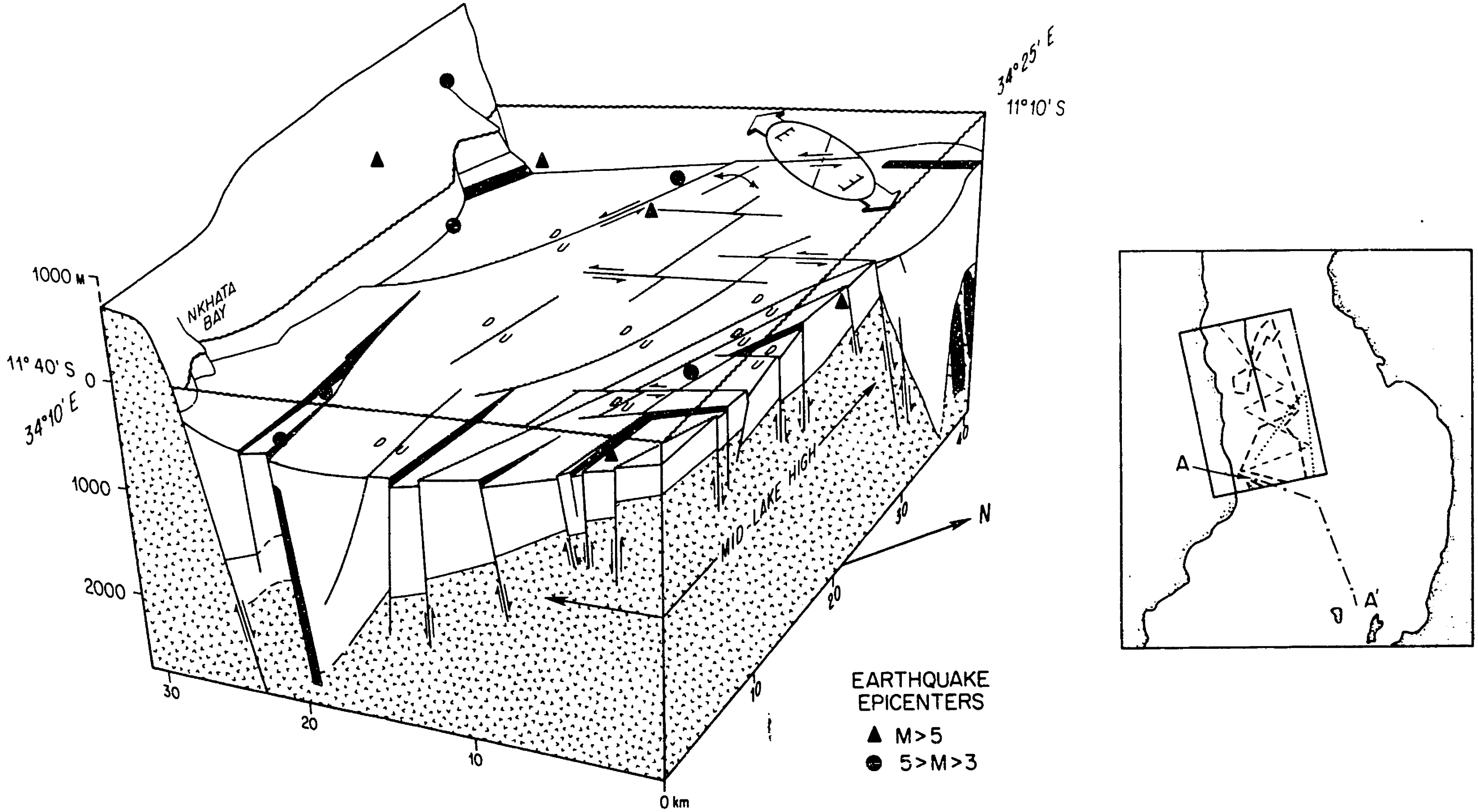
STRUCTURAL PROVINCES
KARONGA
NKHATA
NKHOTA-KOTA
MONKEY BAY
EAST AFRICAN RIFT LAKES
10°
0°
10°
LAKE MALAWI
30°
40°
0
50 km
N
TRACKLINE A-A'
BOUNDARY FAULTS
MODERN FAULTS
DIAPIRS
MESOZOIC FAULTS
HOT SPRINGS
MONOCLINES

Figure 1.


34°25' E
11°10' S
1000 M
NKHATA BAY
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2000
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30
40
MID LAKE HIGH
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▲ M>5
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A
A'

Figure 2.

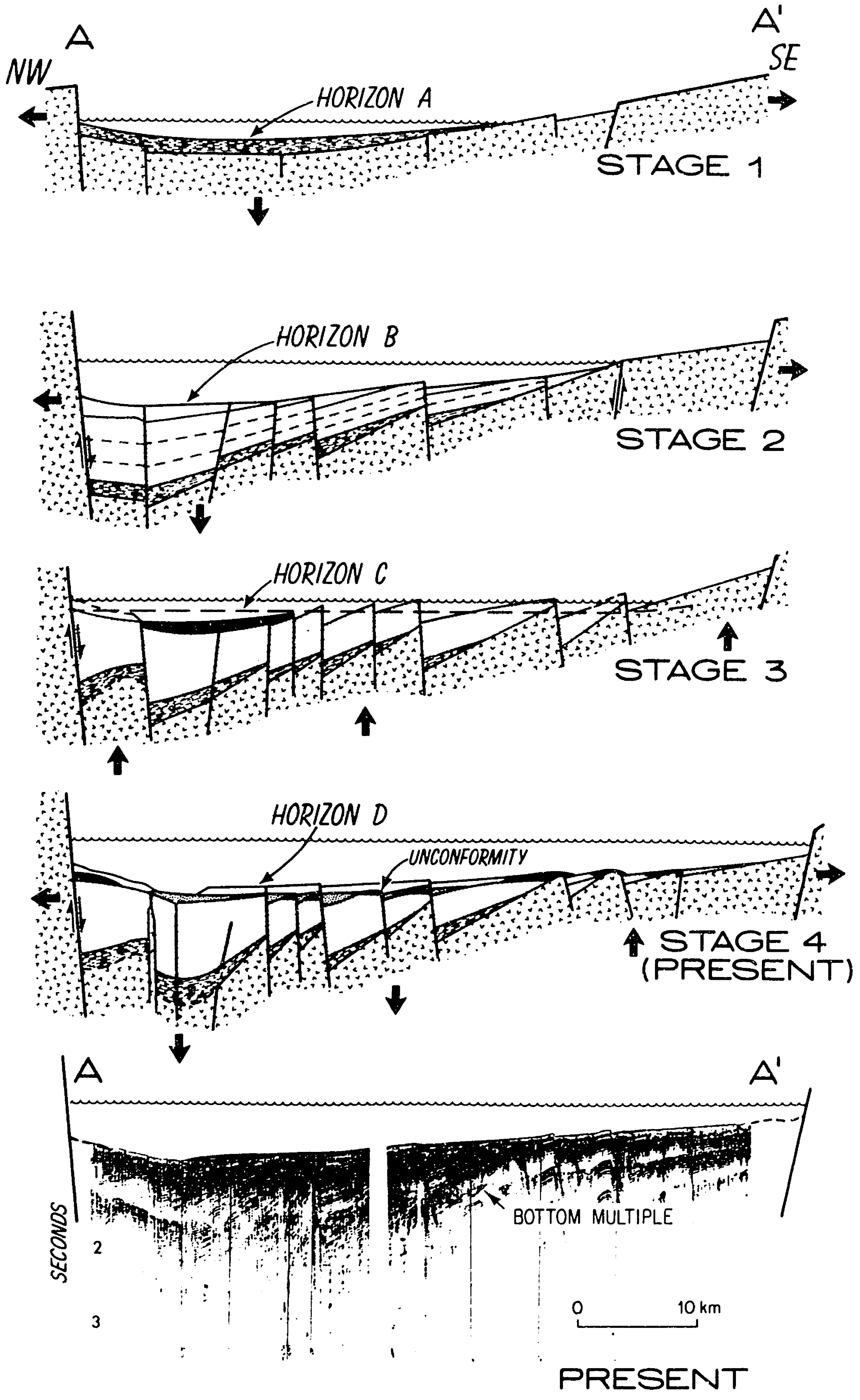
A
A'
NW
SE
HORIZON A
STAGE 1
HORIZON B
STAGE 2
HORIZON C
STAGE 3
HORIZON D
UNCONFORMITY
STAGE 4
(PRESENT)
A
A'
BOTTOM MULTIPLE
SECONDS
2
3
0
10 km
PRESENT

Figure 3.

Figure 1. Tectonic map of Lake Malaŵi region (lakeshore shaded for clarity) showing the principal structural provinces that comprise the lake basin. Faults with large offsets roughly defining the sedimentary basins are designated as Eastern Boundary Fault (EBF) and Western Boundary Fault (WBF). Note these occur within the monoclines bounding the Malaŵi Rift Valley. PC denotes location of 13-m piston core. Symbolism as follows: Diagonal line pattern - Mesozoic sediment troughs; Random dashes - Rungwe Volcanics.

Figure 2. Schematic block diagram depicting the major structural elements of the southern Nkhata Province. (Interpretation based on seismic reflection profiles shown in inset). Strain ellipse superimposed on lake surface indicates approximate orientation of principal strain axes inferred from fault geometries. Faults with a NE trend correspond to planes of high shear strain, and N-S trending faults lie along planes normal to the principal extension direction. Epicenters of earthquakes of magnitude 3 or greater (1966-1977) are shown in their approximate locations. Symbolism as follows: Random V's - crystalline basement; d- diapirs; and Blank - lake sediments.

Figure 3. Four-stage evolutionary sequence envisioned for trackline A-A' (see Figure 1). Vertical scale in seconds two-way travel time. Horizontal extent approximately 70 km. Horizons A-D refer to seismic horizons used as datum in the reconstructions. Arrows denote relative movements within the lake (see text for explanation). Symbolism same as Figure 2.

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Tectonic Model of the Malaŵi Rift, Africa

C. J. Ebinger[1], B. R. Rosendahl[2], D. J. Reynolds[3]

[1] MIT/WHOI Joint Program in Oceanography, Woods Hole, MA 02543

[2] Project PROBE, Dept. of Geology, Duke University, Durham, NC 27706

[3] Exxon Company, USA, Oklahoma City, OK 73106

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INTRODUCTION

Continental rift zones generally are characterized by deep sedimentary basins bounded by steep escarpments, high seismicity, and alkaline volcanism, and are regions underlain by thin crust and elevated lithospheric geotherms. Recent studies have revealed that the systems of normal faults forming the rift escarpments (border fault systems) are segmented along their length (Crossley and Crow, 1980; Zorin, 1981; Cape et al., 1983; Baldridge et al., 1984; Ebinger et al., 1984; Smith and Bruhn, 1984; Bosworth, 1985; Rosendahl et al., in press). Because of this segmentation, rift valleys comprise a series of discrete structural basins bordered by approximately 100km long fault segments. Typically, continental rift basins are bordered along one side by a system of normal faults showing large vertical displacements. Structural relations in rifts indicate that the high-angle border faults become low-angle detachment faults or shear zones at depth (e.g. Wernicke and Burchfiel, 1982), and rheological considerations of extended continental crustal materials support these observations (e.g. Kligfield et al., 1984). It is generally agreed that extension occurs along these normal-slip detachments, hence the original location and orientation of border fault segments influences later stages of rifting and passive margin development. The opposite side of the rift is bordered by a monocline, broken by outward-tilted step faults with minor vertical offsets, or by a monoclinal flexure, producing a half-graben basinal morphology. This structural asymmetry appears to be a ubiquitous feature of extended continental crust; asymmetric sedimentary basins typify active and ancient continental rifts (Bally, 1982;

Reynolds, 1984), and conjugate passive continental margins generally reflect a structural asymmetry (Lister et al., 1986).

Significant variations in cross-sectional profile also occur along the length of continental rifts (Ziegler, 1978; Anderson et al., 1983; Reynolds, 1984; Bosworth, 1985). The side of the rift bounded by a steep border fault system (rift mountains) often alternates to the opposite side of rift valleys at approximately 100 km intervals, or from basin to basin (Chenet and Letouzey, 1983; Reynolds, 1984; Bosworth, 1985; Aldrich, 1986; Rosendahl et al., in press). Cross-fault systems (Gibbs, 1984) or multiple-slip fault systems (Aydin and Reches, 1982) accommodate differential movements between extensional fault segments.

Several three-dimensional models have been proposed to explain the segmented border faults and alternating asymmetries of cross-sectional profiles observed along the length of continental rifts and passive continental margins. Differences between the various tectonic models of continental rift basins largely stem from the geometry in which these border fault segments or rift basins are linked within a rift system. In a recent model of passive margin development, Lister et al. (1986) describe a system of rhomb-shaped basins linked by transfer fault zones that are orthogonal to straight segments of border fault systems (Figure 1A). The tilt direction of fault blocks within basins bounded by border fault segments with opposite asymmetries also reverses. Alternatively, tectonic models of the Gulf of Suez (Chenet and Letouzey, 1983), the Tanganyika rift (Reynolds, 1984), the Keewenawan rift, and the Kenya rift (Bosworth, 1985) employ a series of spoon-shaped border faults that are curvilinear in plan view (Figure 1B).

The purpose of this report is to describe systematic variations in the geometry of rift border fault systems along the length of the Malawi rift system, to illustrate the relationship between basinal morphology and the linkage of border fault segments, and to present possible explanations for the observed along-axis segmentation. In this geometrical classification of structural patterns, the location of border fault systems, their spatial arrangement, and the cross-sectional morphology of basins are used to interpret structural patterns in the Malaŵi rift, part of the Western Branch of the East African rift system (Figure 2). We use existing seismic reflection data from Lake Malaŵi to interpret recently acquired aeromagnetic data, to correct heat flow values measured in a previous study for sedimentation effects (Von Herzen and Vacquier, 1967), and to synthesize these data to update and expand earlier models of Malaŵi rift structures (Crossley and Crow, 1980; Ebinger et al., 1984). This discussion of the Malaŵi rift focuses on the surface geometry of major faults involving crystalline basement; the current data base from the Malaŵi rift is inadequate to address the questions of border fault geometry at deeper crustal levels.

Several explanations for the observed structural segmentation of the Western Branch rift system have been proposed. Previous researchers noted a correlation between Precambrian to Mesozoic structural trends and the outline of the Malaŵi Rift, and they suggested that Neogene faults reactivated ancient zones of weakness (Dixey, 1956; Bloomfield and Garson, 1965; McConnell, 1972). In their studies of structural patterns in the Basin and Range province of the U.S., Smith and Bruhn (1984) suggest that the location of displacement transfer zones corresponds to major structural and lithological boundaries between regions with variable crustal thicknesses. This interpretation would imply that the segmentation of border fault systems and the development of sedimentary basins has been controlled by lateral heterogeneities in the continental crust.

Alternatively, the repetitive length scales and spatial arrangement of border fault systems in the Tanganyika rift and other continental rifts (e.g. Reynolds, 1984) may reflect variations in the amount of lithospheric extension along the length of the rift system, or an along-axis propagation of rifting. We use the tectonic model of the Malaŵi rift discussed below to examine the relationship between Precambrian to Mesozoic structures and the development of border fault systems bounding the Malaŵi Rift. In a concluding section, we compare patterns in the spatial arrangement of border fault segments to observations along oceanic spreading ridges, and discuss possible mechanisms for the regular segmentation.

MALAWI RIFT TECTONIC SETTING

The Malaŵi rift extends over 900 km from the Rungwe volcanic province south to the Urema graben in Mozambique and is situated at the southwestern margin of the approximately 1000m high Tanganyika plateau. The rift valley maintains a fairly constant elevation of 500m (lake-level) from north to south where the valley floor descends to 100m (Dixey, 1937). Continuity in topographic, free-air gravity (Bowin et al., 1982) and seismicity trends (Fairhead and Stuart, 1982; Bungum and Nnko, 1984) indicate that the seismically active Malaŵi rift is a southern extension of the Western Branch of the East African rift system (Figure 2). Seismic (Nolet and Mueller, 1982) and gravity data (Fairhead and Reeves, 1977; Brown and Girdler, 1980) indicate that the crust and/or lithosphere beneath the Western Branch has been thinned. In contrast to the extensive magmatism characteristic of the Kenya Rift to the east, volcanism in the Malaŵi Rift is restricted to alkalic volcanics at the northern end of the lake (Harkin, 1960).

Malaŵi rift structures are thought to be younger than the late Miocene for several reasons, but no direct evidence is available to date the initiation of rifting in this part of the rift system. The oldest known sediments associated with recent rifting in Malaŵi are mid-Pliocene sediments found in the northern portion of the rift (Kaufulu et al., 1981). These sediments are intercalated with Plio-Pleistocene volcanics from the Rungwe center (Harkin, 1960). Using a linear extrapolation of present-day sedimentation rates within the lake (Von Herzen and Vacquier, 1967), sediment thicknesses in excess of

1.8 km observed in seismic records from the Malaŵi rift (corrected for sediment compaction) represent a minimum age of 2.0 My. Fault scarps bounding the rift valley displace a regional mid-Miocene erosional surface (Lister, 1967), which also supports a post-Miocene age assignment. Exposed lakebeds, abandoned shorelines, and drowned river valleys along border fault systems are evidence for recent vertical movements (Stockley, 1948; Crossley and Crow, 1980). Along the shores of the lake, spurs are facetted and there has been little or no modification of fault scarps by waves (Dixey, 1956; Crossley and Crow, 1980).

The flanks of the rift outside the border fault system rise 1200-2500m above sealevel, or 800-2000m above the level of the lake (Figure 3). Vertical displacements along border fault segments measured from a widespread mid-Miocene erosional surface that is taken to be a horizontal datum (Lister, 1967) indicate that the flanks of the rift have been uplifted and are tilted away from the rift valley (Dixey, 1937; Carter and Bennett, 1973). Source mechanisms for earthquakes occurring in the Western Branch are of normal faulting type, and tensional axes are perpendicular to surface faults (Shudofsky, 1985). Epicentral depths within the Western Branch are less than 20 km, and average 12-15 km (Wohlenburg, 1968; Fairhead and Stuart, 1982; Shudofsky, 1985).

Seismic reflection data from within the Malaŵi rift reveal faults often separated by less than a kilometre penetrating both sediments and basement, and few faults extend from one province into the adjoining basin (Ebinger et al., 1984). The seismic reflection profile shown in

Figure 4 was collected parallel to border faults in the Nkhata basin (Figure 2), and illustrates the extent of along-strike variations occurring within the Malaŵi rift. The complicated structure at the northern end of this profile may be one of several "flower" structures observed in the seismic records, and is taken as evidence for transcurrent or wrench faulting (e.g. Harding and Lowell, 1979). Along-strike variations in depositional sequences and fault patterns suggest that segments of the Malaŵi rift have developed diachronously (Ebinger et al., 1984). For the purpose of discussion, these differences have been used to divide the rift into five structural provinces that will be referred to throughout the text: Karonga, Nkhata, Nkhotakota, Monkey Bay, and Shire regions (Figure 5).

Earlier interpretations of Malaŵi rift structures primarily have been based on observations from the western (Malaŵi) side of the rift where seismic reflection and gravity data have been collected (Figure 2). In this study, we have compiled geological information on faults bounding the rift, recently acquired aeromagnetic data, and seismic data to delineate border fault segments and basinal morphologies within the Malaŵi rift. A comparison to geometrical associations between border fault systems and cross-sectional profiles apparent in the model of the Tanganyika rift provides additional insights into Malawi rift structures.

MALAWI RIFT BORDER FAULT SEGMENTS

Neogene faults mapped onshore that displace the mid-Miocene erosional surface and faults beneath Lake Malaŵi have been compiled and used to delineate border fault segments in the Malaŵi rift (Figure 5). Aeromagnetic anomaly patterns are highly variable along the length of the Malaŵi rift, but the axial zone of lineated highs and lows associated with magmatic intrusions in other continental rifts (e.g. Ramberg and Morgan, 1984) is not apparent in data from the Malaŵi rift. Based on a correlation of seismic reflection and magnetic data (Malaŵi Geologic Survey, internal report), nearly all lineated magnetic anomalies are associated with faults identified in the seismic records. We have used aeromagnetic data from the western and southern portions of the rift (Figure 2) to constrain the orientations of faults observed in seismic profiles and in the Shire province south of the lake (Figure 5).

Gravity profiles of the Malaŵi rift zone are characterized by a long wavelength (~100 km) Bouguer gravity anomaly (Brown and Girdler, 1980). Shorter wavelength Bouguer anomalies superimposed on the broad gravity low (Andrew, 1974) provide additional constraints on the geometry of faults within the southern basins of the Shire province (Figure 5). These data were used to determine the sense of asymmetry within the rift basins to the south of Lake Malaŵi, where little information on subsurface structures is available. In our tectonic analysis of Malaŵi rift border fault systems, detailed (2 fm contour interval) bathymetric charts (Yairi, 1977), topographic relief along the rift flanks, and previously mapped faults (McKinlay, 1954; James, 1956; Harkin, 1960; Quennell et al., 1956; Afonso, 1976) were the principal data base used along the eastern side of the rift. A Landsat-5 Thematic Mapper image was used to extend observations into the rugged region between Lake Malaŵi and the Rungwe volcanic province at the northernmost part of the rift (Figure 2). The location of monoclines or step faults is also important in the identification of border fault segments, as these structures generally are found opposite major border fault systems in the Tanganyika Rift (Reynolds, 1984; Burgess, 1985). Because of the subdued topographic relief on the monoclinal side, the presence of rivers with extensive drainage basins and lacustrine deltas also have been used to identify the flexural or shoaling side of a basin.

In the following section, we provide a brief description of the eleven border fault segments (BFS) comprising the Malaŵi rift, referred to as BFS 1-11 (Figure 3) and the morphology of rift basins bounded by these segments (Figure 5). The geometry of border fault linkage in transfer fault zones (Gibbs, 1984), or accommodation zones (Bosworth, 1985; Rosendahl et al., in press), will be discussed in a later section.

In the northernmost part of the rift, vertical movements along several closely-spaced faults down-dropped to the west form an escarpment that rises over 1500m from the surface of Lake Malaŵi (Stockley, 1948; Harkin, 1960). The trace of BFS 1 north of the lake is clearly marked by triangular fault scarps in high resolution (<30m) satellite imagery. To the south where the lake follows a N-S trend, BFS 1 extends onshore with an orientation approximately N30°W (McKinlay, 1954). A deep, lenticular basin at the base of BFS 1 has the cross-sectional form of a half-graben tilted to the east (Figure 3). NNW-oriented monoclines and step faults bound the western side of this rift segment, and several small deltas have formed on the shallow western side (Crossley and Crow, 1980). The proximity of a diapiric structure noted in seismic data from the Karonga area to the Rungwe volcanic center and an associated positive magnetic anomaly suggest that an igneous dike has intruded sediments beneath this part of the lake (Figures 3, 5).

The border fault system immediately to the south, BFS 2, is found on the western side, creating a half-graben that is down-to-the west (Figure 3). The deepest basin within Lake Malaŵi occurs adjacent to BFS 2. Assuming an average sediment velocity of 2 km-s^{-1}, sediment thicknesses observed in seismic profiles from this basin are at least 1.5 kilometres. A fault-bounded basement high was mapped in a detailed survey of the Nkhata region, and the N-S oriented ridge is down-faulted to the north by SW-trending faults (Figure 5). On the opposite side of the lake, eastward-tilted step faults have been mapped onshore (McKinlay, 1954; James, 1956). Subdued topography on the eastern side of the rift is indicated by the entrance of the Ruhuhu River, and bathymetric data suggest a small fan has formed at the mouth of the river (Figure 3).

Although little information is available from the eastern side of the rift in the Nkhata region, we interpret a major border fault system (BFS 3) lying southeast of BFS 2. Based on fault patterns described by Quennell et al. (1956) and Crossley and Crow (1980), BFS 3 appears to be a single fault that curves from NW to a NNW orientation near the widest part of the lake. The basement ridge in the central part of the Nkhata basin separates a narrow basin on the eastern side from the westward tilting half-graben bounded by BFS 2.

BFS 4 occurs on the western side of the rift south of BFS 2 and contributes to the bend or kink in the rift outline. Faults with several orientations occur within this region, but both gravity data onshore (Andrew, 1974) and magnetic data reveal a subset of structures with a WSW trend. The lineated magnetic pattern correlates with closely-spaced faults with minor vertical displacements, and with "flower" structures within the sedimentary sequences (e.g. Figure 4). We interpret structures with a SSW trend as strike-slip faults in an "accommodation" zone between the Nkhata and northern Nkhotakota extensional segments. The sense and amount of horizontal displacement is unconstrained by the seismic data, but magnetic anomaly patterns reveal an apparent right-lateral offset of N-S oriented structures. Crossley and Crow (1980) indicate there is no evidence onshore for recent displacement along shear zones bounding granulitic rocks to the west of the rift (Haslam et al., 1980); hence extension appears to be restricted to the rift valley bounded by the border fault segments.

BFS 5 is on the eastern side of the rift and bounds a half-graben tilted down to the east. This part of the rift is dominated by N-S oriented structures that also are apparent in aeromagnetic data from the Nkhotakota region. Fault-bounded rift mountains on the eastern shore rise approximately 1100m above the lake (Afonso, 1976). An approximately 60 km long monocline occurs on the western side of the lake (Crossley and Crow, 1980), and several deltas have formed at the mouths of the Bua and Dwangwa Rivers (Figure 3). Faults in the Nkhotakota region are more widely-spaced across the rift than in the northern two provinces (Figure 5), and limited seismic data reveal over 1 km of sediments within the western part of this eastward-tilted basin.

South of BFS 5, water depths are shallower, and the half-graben morphology characteristic of the northern basins is less evident. These observations suggest that the Nkhotakota and Monkey Bay provinces (Figure 5) may be younger than the Karonga and Nkhata segments. In contrast to the fairly smooth, elongate magnetic anomalies observed in the two northern provinces, isolated, shorter wavelength anomaly patterns are found in this region, which may indicate that crystalline basement is shallower in the southern basins (Malaŵi Geologic Survey, internal report). Along the shores of the lake south of BFS 5, faults with NNW and SSW trends (~ 30° to one another) form a zig-zag border fault system (Figure 5) that contrasts with the more curvilinear outline of BFS 1-5. Based on changes in sediment thickness and differences in the geometry of faults bordering the lake, we predict that a second border fault segment, BFS 6, extends along the eastern side of the lake south of BFS 5. The narrow, eastward-tilted basin defined by this border fault segment continues to the narrowest part of the lake separating the Nkhotakota from the Monkey Bay region.

In the Monkey Bay province, a NW-oriented border fault system (BFS 7) bounds the eastern arm of Lake Malaŵi. Bathymetric data (Yairi, 1977) show this shallow basin has a slight tilt to the west. BFS 8 is a NNW-trending fault system bounding a westward-tilted basin. The southwestern portion of this border fault segment is a single scarp that rises nearly 1000m above sediments on the lakeshore plain near the central part of BFS 8, and there is a progressive decrease in elevation of this segment both to the north and south (Walter, 1967; Thatcher, 1968). A 10 km shelf, back-tilted to the west occurs immediately to the east of BFS 8.

Three additional border fault segments occur south of Lake Malaŵi. A fault system with a N-S orientation on the eastern side of a small lake forms BFS 9. In plan view, the concavity of BFS 8 is opposite to that of BFS 9, and a NNW-trending fault-bounded ridge separates these two rift basins (Figures 3, 5). A SSW-oriented escarpment, BFS 10, on the southeastern side of the rift contributes to the sinuous outline of the southern Malaŵi rift, and a faulted monocline is found opposite BFS 10. Gravity data (Figure 5) indicate that the sense of asymmetry shifts from down-to-the-east along BFS 9 to down-to-the-southeast in the half-graben bounded by BFS 10 (Figure 5). The focal plane of an earthquake along the flexural side of the basin bounded by BFS 10 indicates the axis of least compressive stress is N40°E, or parallel to the Zomba escarpment (Figure 5). Over 1000m of vertical displacement have occurred along BFS 11 to form a half-graben asymmetric to the SE (Crossley and Crow, 1980), and a 2-12 km wide platform tilted to the east is found at its base (Dixey, 1937). Malaŵi rift movements have warped a Mesozoic (Karroo) basin opposite BFS 11 into a monocline or low scarp (Wooley and Garson, 1970).

TECTONIC MODEL

The observed geometry of border fault systems and variations in structural patterns within the Malaŵi rift have been used to construct the stylized tectonic model shown in Figure 6. We compare border fault geometries and spacings of Malaŵi rift basins to a tectonic model of the Tanganyika rift (Rosendahl et al., 1986) in order to propose explanations for the observed segmentations.

From the structural analysis of border fault segments in the Malawi rift, discrete changes in the orientations of faults comprising each border fault segment result in a regionally curvilinear border fault segment. Similar curvilinear "master" fault systems and half-graben rift morphologies have been produced in clay model experiments of extension (Stewart, 1971; Elmohandes, 1981). Vertical displacements along border fault segments are usually greatest near the central the segment. For example, in the Karonga and Nkhata regions of the Malawi rift, prominent rift mountains border deep lozenge-shaped sedimentary basins (Figure 7). The spatial arrangement of these curvilinear border fault systems produces the sinuous rift valley shown in Figure 7.

In the southern part of Lake Malaŵi and in other rifts (Dixey, 1959; Freund, 1982), criss-crossing faults form rhomb-shaped fault blocks and a zig-zag border fault system (Figure 5). If the border fault segments in the southern part of the rift are more youthful than those in the Nkhata and Karonga provinces, zig-zag border fault systems may evolve to curvilinear border fault segments, such as BFS 1 and BFS 2 in the Malaŵi rift, and in the Tanganyika rift, during successive episodes of rifting.

Consistent geometrical patterns apparent in this model of the Malawi rift indicate that the arrangement of border fault segments largely determines basinal morphologies; we describe several of the geometric relations below. Examples used to illustrate the spatial arrangement of Malaŵi rift border fault segments and their association with a distinct cross-sectional morphology are designated by upper case letters in Figure 6. These results provide a framework to distinguish between tectonic models of continental rift systems.

BORDER FAULT LINKAGE

The alternation of border fault segments across the rift and associated "flip-flopping" of basinal asymmetries produces complicated fault patterns where border fault segments abut or overlap. However, several consistent patterns emerge from this synthesis of data from the Malawi rift and comparison to patterns observed within the Tanganyika rift. Examples of geometries discussed in the text are designated by upper case (Malaŵi rift) and lower case (Tanganyika rift) letters in Figure 6. The geometry of border fault linkage illustrated in Figure 1B occurs where border fault segments with opposite senses of concavity abut one another to form an S-shaped geometry. In Lake Malaŵi, a shallow fault-bounded ridge occurs where BFS 5 and BFS 7 extend beneath the lake and are linked end-to-end (A). Segments 5 and 7 are sub-parallel with opposite senses of concavity, producing a sigmoidal rift valley and alternating basinal asymmetries. Because the ridge is oriented oblique to the trend of the rift valley, cross-sectional profiles vary along the length of the rift basin where the ridge occurs. In the Tanganyika rift basement ridges are observed where border fault systems have a similar geometry (a, b). The abutting half-graben geometry is analogous to the San Luis and Espanola basins in the Rio Grande rift where two half-graben with opposing asymmetries are linked by the Jemez volanic lineament (Aldrich, 1986).

Two border fault systems with opposite concavities that face one another (across the rift) produce the archetypal rift profile of a full-graben, a morphology that is exceptional in the Malaŵi and Tanganyika rifts. This basinal morphology is produced by the juxtaposition across the rift of two half-graben with opposite senses of asymmetry (Rosendahl et al., in press). Elevated basement ridges or buried axial antiforms trending parallel to the border fault systems are usually associated with full-graben cross-sectional morphologies. For example, a NNW-oriented ridge occurs in the central part of Lake Malaŵi where BFS 2 and BFS 3 face one another across the rift (B). Similarly, full-graben with axial ridges occur in the central (C) and southern parts of the Malaŵi rift (D) and at locations (c) and (d) in the Tanganyika rift. In both rifts, the structural high separating the two facing half-grabens appears to function as a hinge for subsidence in the half-graben on either side. This type of geometry prompted Rosendahl et al. (in press) to describe these features as "hinged highs".

The geometry of later-stage faults within the sedimentary sequences of rift units, such as the mid-lake high in the Nkhata basin, indicates continued movements may produce structural re-orientations and local uplift. For example, depositional patterns within the Nkhata region (B) indicate the central horst was once part of the sedimentary basin bounded by BFS 2, and that this ridge has only recently been uplifted relative to the Nkhata basin.

Shallow platforms, or back-tilted fault blocks, adjacent to border faults are found at the junctions of border fault systems and monoclines (E, F, G), or where the tips of two border fault segments are linked on the same side of the rift (H, I, J, K). Similar relations are observed in the Tanganyika rift at locations (e, f) and (g, h). In both the Malaŵi and Tanganyika rifts, platforms are generally triangular in plan view. Three-dimensional space considerations in the rift basin model explain back-tilted platforms as blocks pinned where border fault systems and flexural boundaries intersect (see Figure 1B).

The three-dimensional aspects of the Malaŵi rift model are capable of explaining observations of extensional and strike-slip structures within a regionally extensional environment. These movements are related both to differential motions or strain accommodations between rift segments and, more locally, along the zig-zag border fault systems (Figure 5). Beneath Lake Malaŵi, folded sedimentary layers and closely-spaced faults with little vertical displacement bound the buried ridge at (A) and at (a) in Lake Tanganyika, and these differential motions are consistent with space requirements between two extensional segments. With continued extension, interbasinal regions could become sites of large transcurrent movements. Depositional and rotational patterns of fault blocks interpreted from sedimentary sequences and reconstructions of basement faults (e.g. Gibbs, 1984) provide indirect evidence that these major border fault segments are listric, but there is no direct evidence to constrain the geometry of border faults within the crust.

INFLUENCE OF PRE-EXISTING STRUCTURAL TRENDS

We have summarized the tectonic history of this region as shown in Figure 8 to examine the role of ancient structural trends on the development of Malaŵi rift basins. Faults attributed to the Malawi rift formed in Proterozoic to Precambrian mobile belts on the western and southwestern margins of the Tanganyika shield. During the Ubendian orogeny (1800-2250 My) deformation occurred in a belt of tightly-folded rocks with northwest-trending fold axes (Fitches, 1970). Along the northeastern side of the Karonga region, a discontinuous lineament of basic and ultrabasic rocks, in thrust fault contact with underlying Ubendian rocks (Stockley, 1948), is interpreted as a suture zone that closed during the Kibaran orogeny (1300 My). Basement rocks on the western margin of the Malaŵi rift were folded along NE-SW axes during the same period (Carter and Bennett, 1973). On the eastern margin of the Malaŵi rift, rocks with a N-S grain were deformed during the Mozambiquian orogeny (400-700 My; Cannon et al., 1969). Foliation directions indicate parts of the Ubendian and Kibaran orogenic belts were overprinted during the Mozambiquian orogeny, and widespread outcrops of granulites and migmatites occur within this belt (Carter and Bennett, 1973).

Several fault-bounded sedimentary basins containing Permo-Triassic (Karroo) sediments and volcanics occur near or within the boundaries of the rift system (Figure 8). In the northern Nkhata region, the subdued character and SW-trend of magnetic anomalies (Malaŵi Geologic Survey, internal report), and a change from highly reverberant acoustic basement to discontinuous reflectors in seismic profiles indicate that

Permo-Triassic Karroo sediments exposed onshore in the Ruhuhu Trough extend beneath the lake. In the southern provinces, a NE-trending lineament of alkaline plutons and dikes within a narrow graben was emplaced during a Jurassic-Cretaceous phase of rifting (Wooley and Garson, 1970; Carter and Bennett, 1973).

When viewed in a regional framework, both the Malaŵi and Tanganyika rifts have formed in mobile belts and tend to avoid the rocks of the Tanganyikan Shield which may indicate the Western Branch follows a large-scale zone of weakness in the lithosphere. However, Shudofsky (1985) found a fairly homogeneous velocity structure in the lithosphere beneath the Western Branch in a study of seismic body and surface waves generated by earthquakes in East Africa. In our analysis of Malawi rift structures, we have described border fault segmentations that occur with repetitive length scales of 100km, hence we will assess the influence of pre-existing structures at this same length scale. Pre-existing structures are defined as faults, folds, dikes, and gneissic foliation planes in the metamorphic rocks adjacent to the rift that are attributed to these earlier orogenies. In an earlier study of faults along the western flanks of the rift, Crossley and Crow (1980) noted little correlation between Neogene and ancient faults. We have concentrated on regional structural patterns along the northeastern, western, and southern parts of the Malaŵi Rift to examine the influence of Precambrian to Mesozoic structures on the development of border fault segments described in the previous section.

By superimposing the traces of Malaŵi rift border fault segments on the regional tectonic framework (Figure 8), several consistent relationships between the location and orientation of border fault segments can be made. Few (if any) border fault segments follow lithologic or tectonic contacts, and the trace of border fault segments may continue from one tectonic province to another with little change in orientation (e.g. BFS 2). Where the trend of pre-existing structures is subparallel to the regional N-S trend of the Malaŵi rift, some parts of border fault systems follow the trends of older structures (Crossley and Crow, 1980). For example, BFS 1 on the northeastern side of the Karonga Basin is subparallel to Precambrian thrust faults and elongate belts of Proterozoic rocks, but there is little evidence in Landsat imagery or field data (Stockley, 1948) for reactivation of Precambrian thrust faults just to the northeast of BFS 1. It is interesting to note that the basement geology in the northern part of the Malaŵi rift is similar to that found in the Basin and Range province, where some Mesozoic and Tertiary thrust faults have been reactivated as detachments for low angle normal faults (Wernicke and Burchfiel, 1982; Smith and Bruhn, 1984).

The central parts of border fault systems, where the greatest vertical displacements occur, have orientations that usually are oblique to pre-existing structures. For example, BFS 2 is oriented nearly orthogonal to NNW-trending Ubendian structures, BFS 5 cuts across a Karroo trough, and BFS 8 is oriented approximately 60° to the trend of metamorphic fabric. Along BFS 8, open folds and shear zones with axial traces oriented WNW are displaced by Malaŵi rift faults (Inset B, Figure 8). Jurassic-Cretaceous plutons have been truncated by BFS 10, and

BFS 11 cross-cuts granophyre dikes in the southern part of the rift.

In several locations within the Malaŵi rift, subsets of faults located within the border fault systems have orientations parallel to joints or nearly vertical axial planes of gneissic foliations in rocks exposed on the rift flanks. For example, SSW-oriented structures between BFS 2 and BFS 4 parallel shear zones bounding the Champira Dome, although there is little evidence onshore that the faults in this region have been rejuvenated by recent rifting (Crossley and Crow, 1980). In the southern part of Lake Malaŵi, where BFS 8 crosses high-grade metamorphic rocks in the southern part of the rift, some faults follow joints and foliation planes in the short segments forming a rectilinear or "zig-zag" pattern (Figure 8). Regionally, the longer faults with a NNW trend do not follow major zones of crustal weakness or lithologic contacts (Thatcher, 1968).

Summarizing these observations, major boundary fault systems are poorly correlated with pre-existing zones of weakness, and border fault segments do not appear to alternate sides of the rift to "avoid" stronger rock units. In both the Tanganyika and Malaŵi rifts, the terminations of the border fault segments at regular intervals along their lengths and reversals of basinal asymmetries rarely occur at lithologic contacts or at the boundary between tectonic units. An exception may occur between BFS 2 and BFS 4 at the bend in Lake Malawi, as the offset coincides with the high-grade metamorphic unit described above. In interbasinal regions, or accommodation zones, reactivation is more commonly observed where ancient structures have an orientation subparallel to the regional N-S trend of the Malawi rift valley, or at the tips of border fault segments where vertical movements are distributed along a system of closely-spaced faults with minor offsets.

Locally, individual faults comprising the border fault segment may follow joints or foliation planes, particularly where existing structures trend roughly N-S, or parallel to the general trend of the rift. From laboratory tests of pre-strained rocks, rejuvenation of pre-existing fractures may occur where differences between principal stress orientations in successive episodes are small, depending upon the material properties of the rocks (Handin, 1969). With differences in principal stress directions less than 25°, rejuvenation is often observed in metamorphic rocks (Handin, 1969). These results may explain the shift from the N-S trend of the Malaŵi rift between BFS 1 and 2 possible reactivation along BFS 1, where pre-existing structures in the Ubendian belt are oriented approximately 25° to the N-S trend of the Malaŵi rift.

ESTIMATES OF EXTENSION

Generally low terrestrial heat flow values were measured during a reconnaissance survey (Von Herzen and Vacquier, 1967), but these values were not corrected for thermal blanketing effects which tend to depress measured values. Seismic reflection profiles from the western side of Lake Malaŵi were used to correct measured heat flow values (Von Herzen and Vacquier, 1967) for thermal blanketing effects, which tend to depress the measured heat flux from the rift. Core samples from the thermally stratified anoxic lake reveal the upper 13m of sediments are composed of diatomites and muds, and sedimentation rates range from 1-5 mm/yr (Von Herzen and Vacquier, 1967; Muller and Forstner, 1973; Ebinger et al., 1984). Estimates of sedimentation corrections were obtained using a nomogram presented by Hutchison (1985) that relates the variation of heat flux through time for deposition of shales or deep-water marine sediments. The various corrections assume both a constant sedimentation rate and sediment grain conductivity, pore water advection, and changing bulk conductivity with depth due to sediment compaction (Hutchison, 1985). In unsurveyed parts of the lake, a 1.2 kilometre sediment thickness was assumed. Seismic profiles from the Nkhata Province reveal several measurements were made in disturbed sediments interpreted as massive slumps, and these extremely low values were not considered in the re-interpretation (Figure 9). We anticipate the extremely low (<25 mW/m^2) values at the base of BFS 1 have been affected similarly, and have not included these measurements in the compilation.

Based on this graphical comparison, the present heat flow from the Malawi rift has been reduced by 10-30% by the rapid deposition of sediments. The average corrected heat flow value of 75.3 mW/m^2 is higher than the uncorrected mean value of 52.4 mW/m^2, and is above the African continental mean of 49.8 mW/m^2 (Sclater et al., 1980). These data have a large standard deviation (±35 mW/m^2), but both the mean values and variability within the rift are typical of observations within other continental rift systems (e.g. Ramberg and Morgan, 1984).

Much of the scatter in these data is eliminated when the corrected values are grouped with respect to the structural provinces described above (Figures 3, 7). As shown in Figure 9, there is a large difference in mean values between basins bounded by separate border fault systems. Seismic reflection data reveal no correlation between extreme values and local basement highs or faults, indicating that the high values are not caused by pore water expulsion along faults or heat refraction through basement highs (Green et al., 1981). These along-axis variations may be related to hydrothermal circulation patterns within the lake, as numerous hot springs occur along faults bordering the Malaŵi rift (Figure 9), and iron-rich compounds (nontronite) recovered in shallow cores from Lake Malaŵi suggest that hydrothermally active areas occur beneath the lake (Muller and Forstner, 1973). However, the length scales of basinal groupings are much greater than the 5-10 km wavelengths of hydrothermal cells reported in oceanic crust (Green et al., 1981).

We have estimated lithospheric extension within the Malaŵi rift by graphically comparing heat flow and subsidence with values predicted in a one-dimensional, two-layer stretching model presented by Royden (in press). A deep-water sediment factor (Crough, 1983) was used to correct basement depths for sediment loading, and vertical movements have been referenced to a mid-Miocene erosional surface (Lister, 1967). Because the number of values within each of the four extensional segments shown in Figure 9 is small, we have used the mean heat flow value within the rift (75 mW/m^2) to estimate extension within the Malaŵi rift. The average heat flow and subsidence in the Malaŵi rift indicates that both the crust and subcrustal lithosphere have been thinned by approximately 50%. The 5-10 km of crustal extension obtained from reconstructions of fault geometries in the Nkhata basin is much less than the 25 km predicted using the mean value from the rift. However, this value is in good agreement with the 5-20% extension predicted using the basinal heat flow mean for the Nkhata extensional segment (Figure 9).

DISCUSSION

These studies indicate that the major structural components of the Malawi rift are regionally curvilinear border fault segments that are 60-120 km long. Border fault segments bound sigmoidal-shaped basins linked along the length of the rift in accommodation or transfer fault zones. In the Malaŵi and Tanganyika rifts, differential movements in accommodation zones between extensional basins occur along fault systems with minor vertical offsets that trend oblique to border fault segments. In many parts of both rifts, the border fault segments serve to accommodate these movements, producing the sinuous rift outline characteristic of many continental rift systems (Figure 1B). Translational movements between rift segments within the Malaŵi rift occur within the border fault systems, but there is little evidence these strike-slip fault zones continue across the rift flanks and into the adjoining regions. Crustal extension is restricted largely to the rift valley bounded by major border or detachment faults, and suggests that little thinning occurs beneath the rift flanks.

The similarity between patterns observed in the Malawi and Tanganyika rifts indicates that the location of uplifted shoulders on the deep side of asymmetric basins marks the initial position of crustal detachments. With continued extension, these alternating border fault segments or detachment faults may coalesce and the transfer fault regions become sites of large transcurrent motions. The similiarity between structural and morphological patterns within the Malaŵi and Tanganyika rifts, which have formed at different times and in metamorphic rocks of different age and composition, indicate that these geometric relations can be used as predictive tools in other rift systems. We hope this type of basinal classification will be adopted by others to facilitate comparisons between rift systems. Because the three-dimensional model presented in this report does not consider the injection of new material, the geometries we have described may not be directly applicable to other continental rifts characterized by extensive volcanic activity.

The lines of evidence used in this study suggest that the border fault segments are tectonic-scale fractures caused by extensional stress concentrations at discrete intervals along the length of the rift system. The poor correlation between the trends of approximately 100 km long border fault segments and pre-existing structures in the Proterozoic to Mesozoic rocks surrounding the rift indicates that the segmentation of the Malaŵi and Tanganyika rifts is a direct response of continental crust to extension. In this concluding section, we discuss two possible rifting mechanisms that are consistent with the observations of along-axis segmentations and alternating asymmetries within the Malawi and Tanganyika rifts.

The interbasinal differences in sediment thickness, heat flow, and structural style may be temporal, which suggests that the rift has propagated along-axis. With continued episodes of extension, the rift may propagate laterally, additional border fault segments form, and transfer fault systems develop to link extensional segments. For example, the locus of sedimentation within several Tanganyika rift basins has shifted through time, apparently in response to structural readjustments caused by the formation of additional border fault segments (Burgess, 1985). In support of this hypothesis, there is a similarity between the spatial arrangement and linkage of curvilinear border fault segments in the Malawi and Tanganyika rifts and the geometry of propagating oceanic ridge crest segments where they overlap along the length of the rift (Pollard and Aydin, 1984; Sempere and MacDonald, 1986).

Alternatively, the observed regular segmentation may be initiated by a spatially periodic mantle anomaly along the length of the rift. Because many of the border fault systems overlap or oppose one another, we have used the distance between the central part of each border fault segment and the adjoining border fault segment to measure the regular spacing of border fault segments along the rift. The spacings between of border fault segments are nearly identical in the Malaŵi (73±14 km) and Tanganyika (69±10 km) rifts (Figure 6), despite their differences in geologic setting and age of rift initiation. These values may be biased to the high side, as subsurface coverage in both rifts is not complete and additional border fault segments may be found.

Indirect support for a three-dimensional rifting mechanism comes from a comparison to observations of segmentations along oceanic spreading ridges. The 70 km wavelength observed in the Malaŵi and Tanganyika rifts is close to the 50-60 km spacing of axial volcanism along the Red Sea rift, the Mid-Atlantic ridge, and the East Pacific rise (Bonatti, 1985; Schouten et al., 1985). With little information on the structure of the lithosphere beneath the Malaŵi and Tanganyika rifts, we can only speculate on rifting processes producing the spatial arrangement regular spacing of border fault segments. In an experimental model proposed to explain along-axis variations in oceanic ridge magmatism and morphology, a sinusoidal pattern of diapirs developed from a linear gravitational instability of a less dense fluid beneath a more dense fluid (Whitehead et al., 1984). If the mantle beneath the East African rift system is hotter and less dense than the overlying lithosphere, a similar pattern of diapiric upwellings may have caused the regular segmentations observed within the Malaŵi and Tanganyika rifts. A test of this hypothesis for the segmentation of continental rift zones awaits detailed field studies within active continental rifts.

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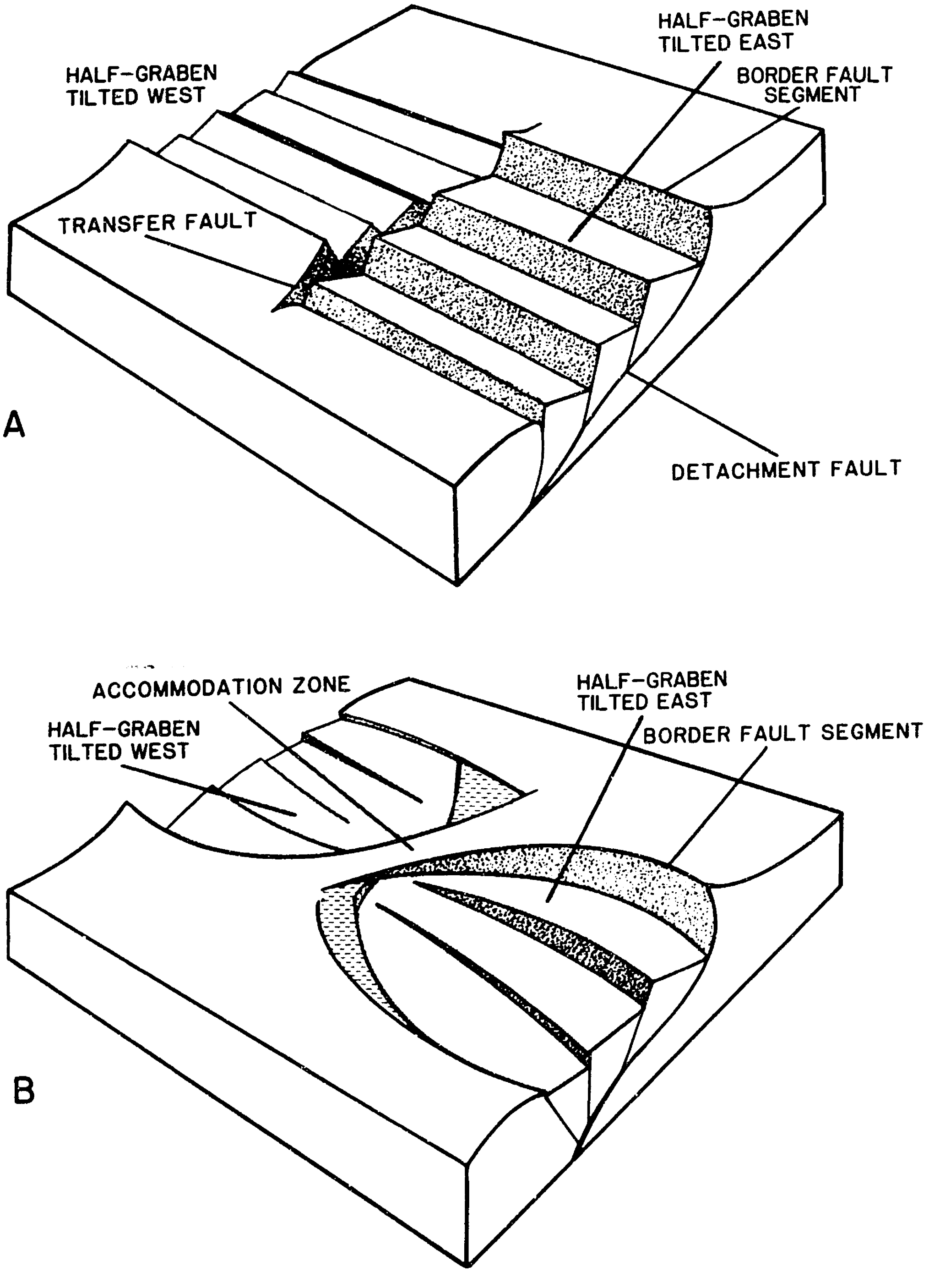

HALF-GRABEN
TILTED EAST
HALF-GRABEN
TILTED WEST
BORDER FAULT
SEGMENT
TRANSFER FAULT
A
DETACHMENT FAULT
ACCOMMODATION ZONE
HALF-GRABEN
TILTED EAST
HALF-GRABEN
TILTED WEST
BORDER FAULT SEGMENT
B

Figure 1.

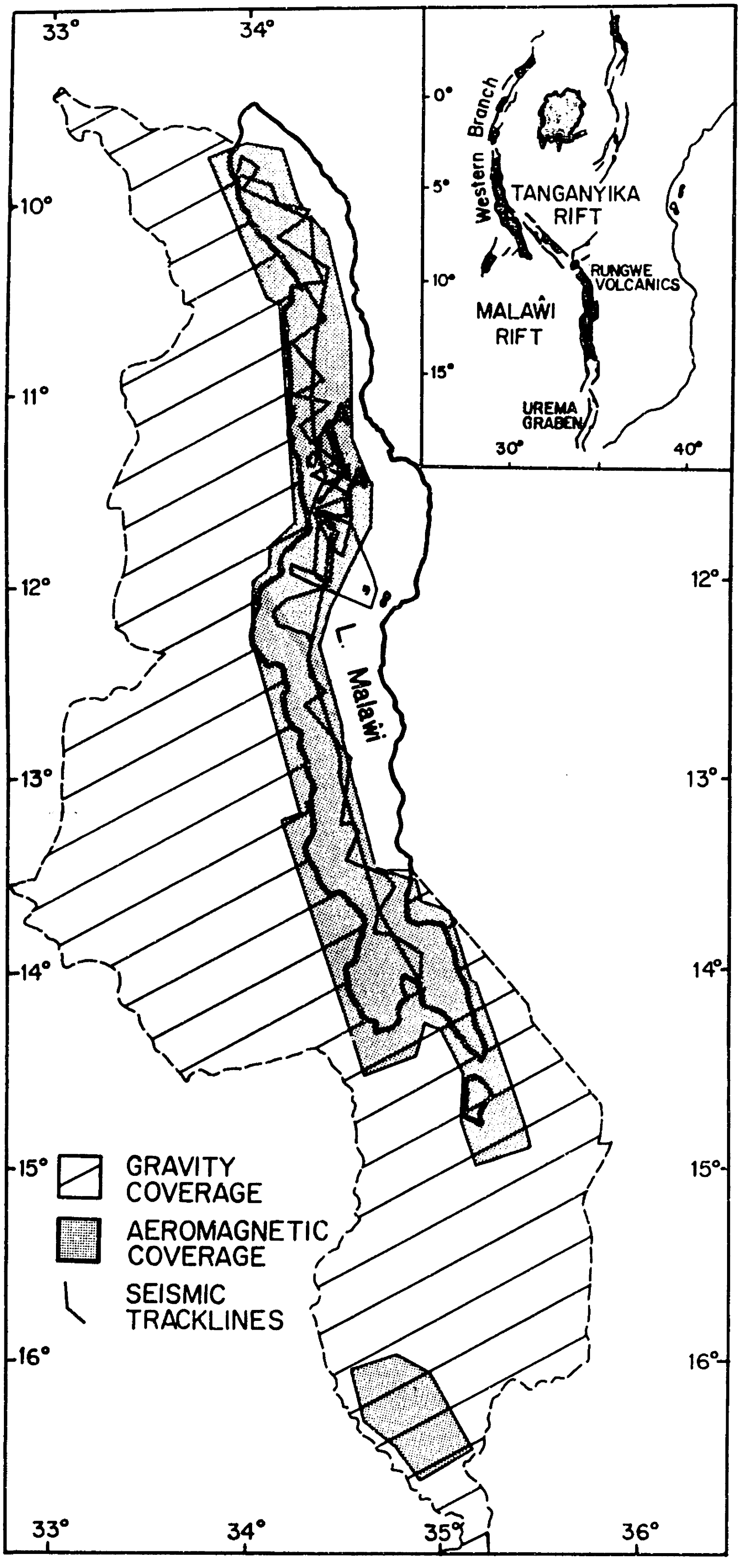

33°
34°
35°
36°
10°
11°
12°
13°
14°
15°
16°
L. Malawi
GRAVITY COVERAGE
AEROMAGNETIC COVERAGE
SEISMIC TRACKLINES
0°
5°
10°
15°
30°
40°
Western Branch
TANGANYIKA RIFT
RUNGWE VOLCANICS
MALAWI RIFT
UREMA GRABEN

Figure 2.

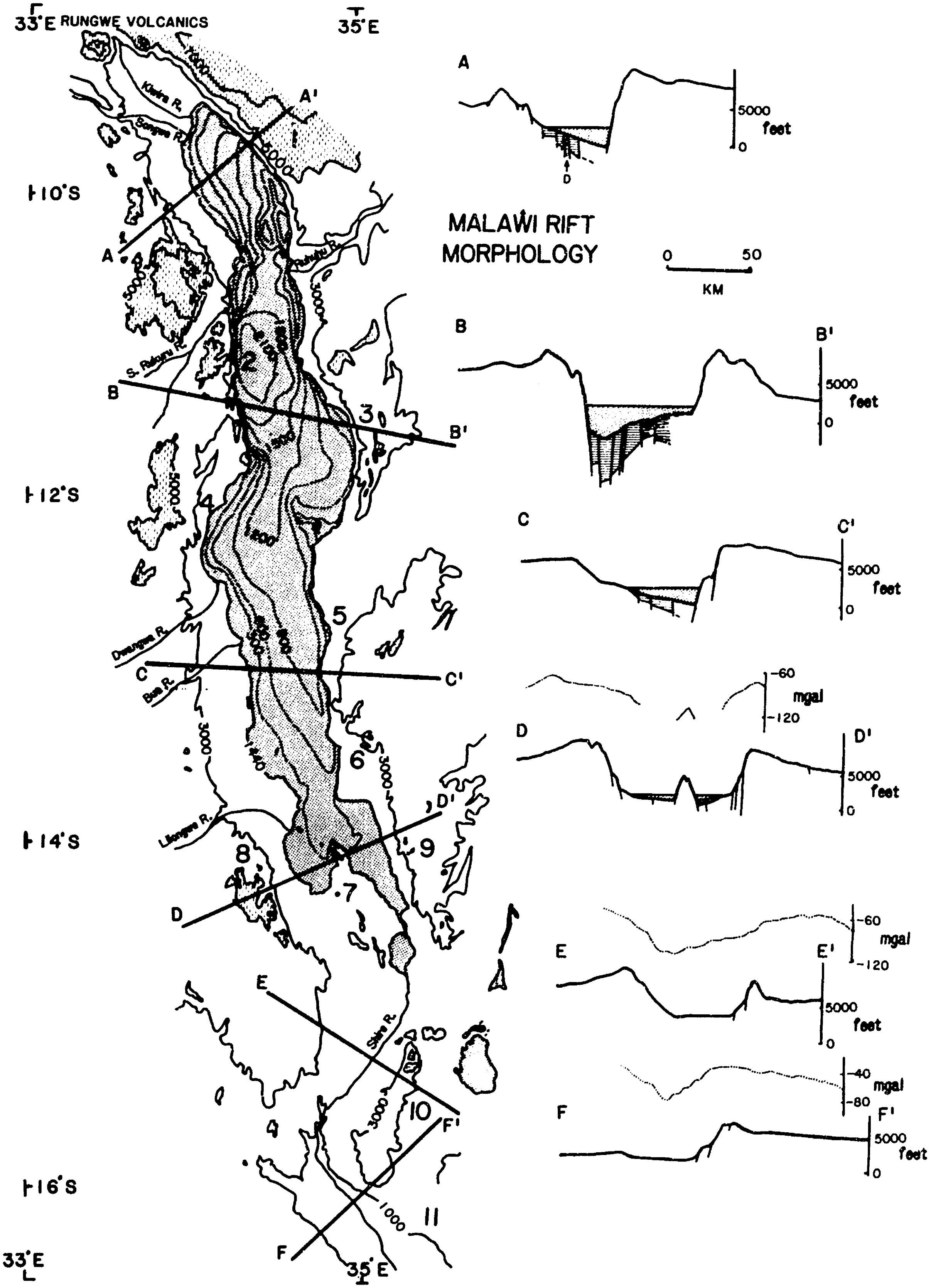

33°E RUNGWE VOLCANICS
35°E
MALAWI RIFT
MORPHOLOGY
0 50
KM
10°S
12°S
14°S
16°S
33°E
35°E
Kiwira R.
Songwe R.
Rukuru R.
S. Rukuru R.
Dwangwa R.
Bua R.
Lilongwe R.
Shire R.
3000
1200
1400
1000
1
2
3
5
6
7
8
9
10
11
A
A'
B
B'
C
C'
D
D'
E
E'
F
F'
5000
feet
0
-60
mgal
-120
-40
-80

Figure 3.

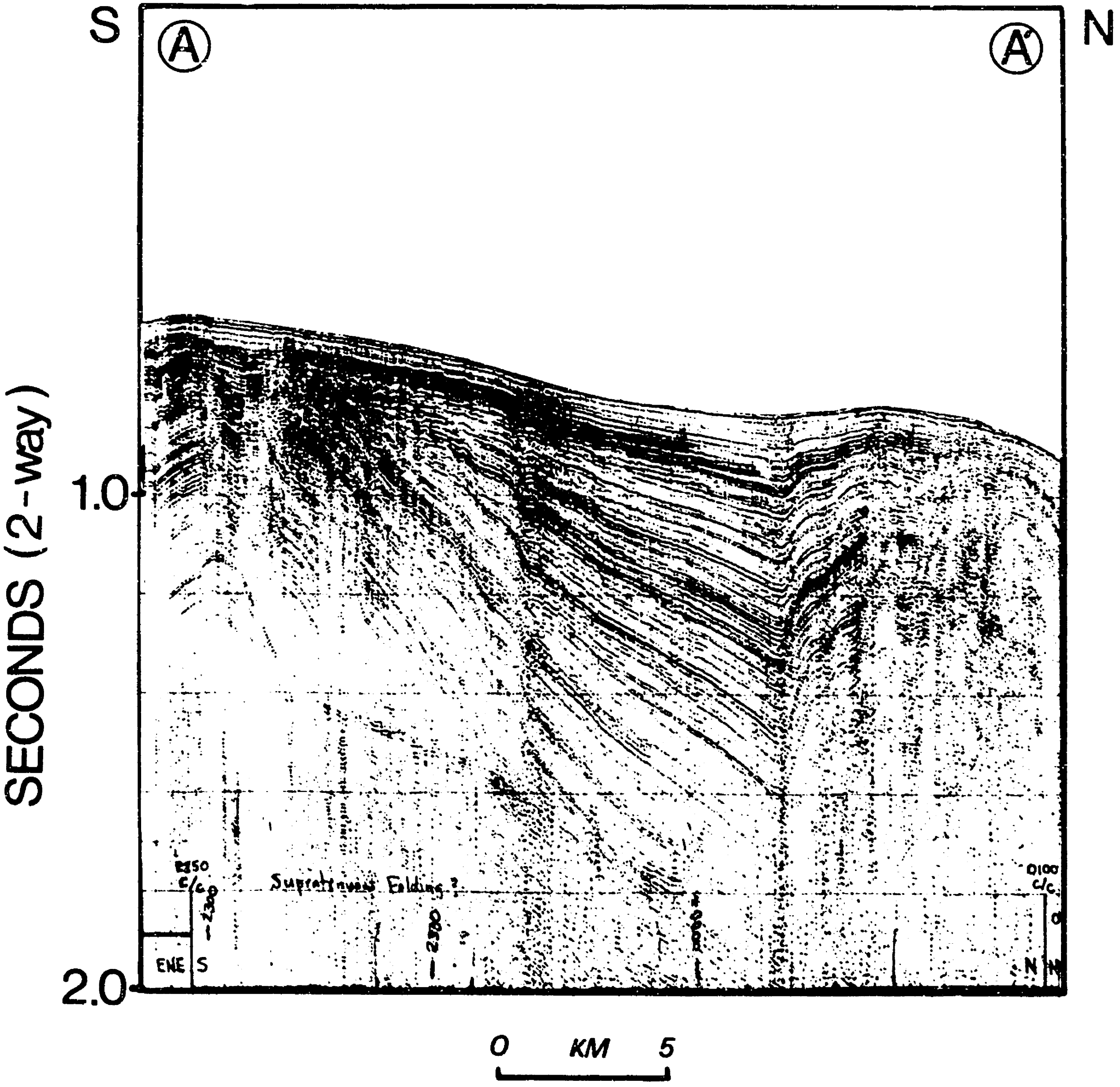

S
A
A'
N
SECONDS (2-way)
1.0
2.0
2350
C/C
Supratenuous Folding ?
2300
2330
0000
0100
C/C
ENE
S
N
0 KM 5

Figure 4.

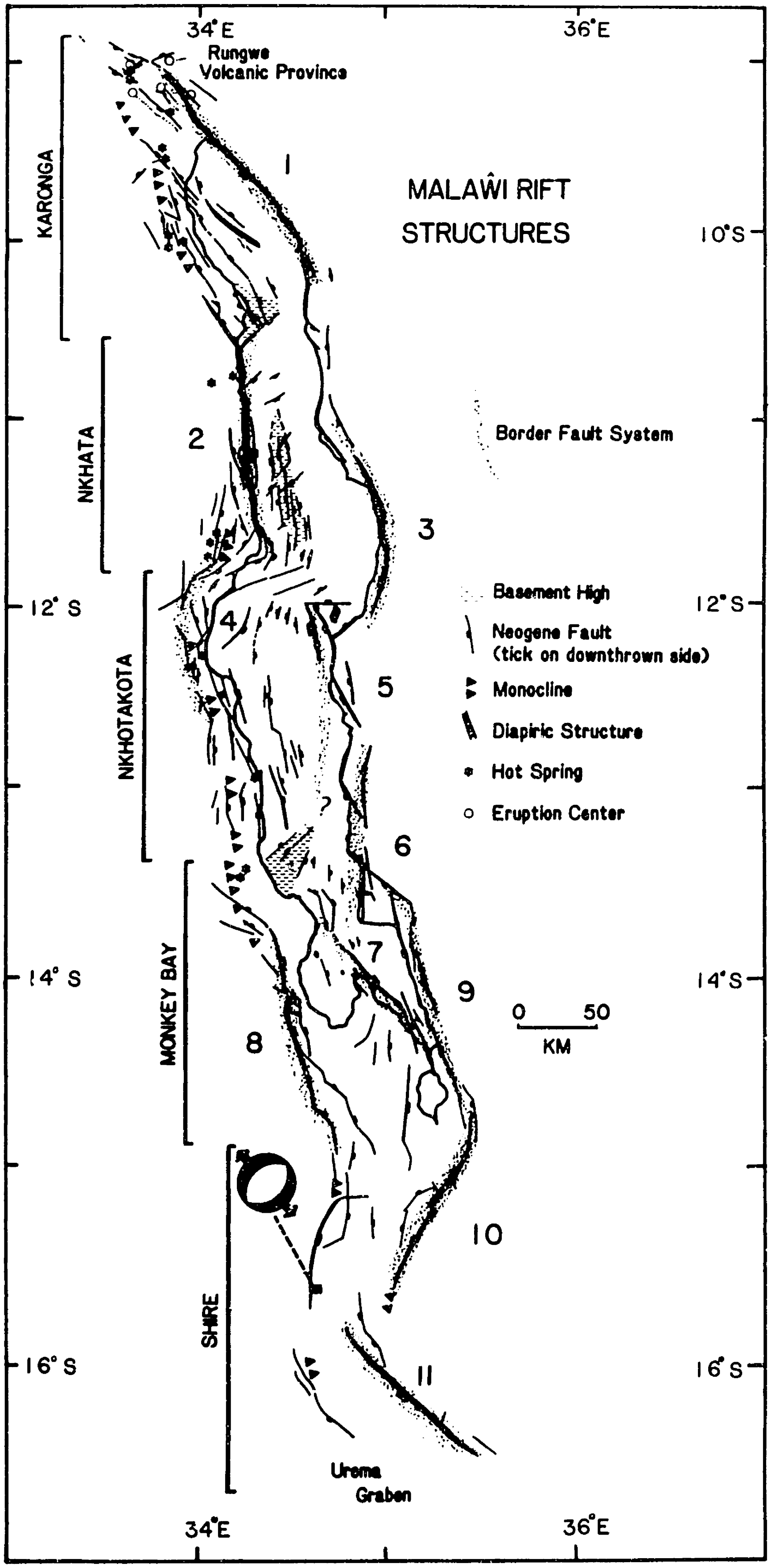

MALAWÎ RIFT
STRUCTURES
34°E
36°E
10°S
12° S
14° S
16° S
Rungwe
Volcanic Province
KARONGA
NKHATA
NKHOTAKOTA
MONKEY BAY
SHIRE
Urema
Graben
1
2
3
4
5
6
7
8
9
10
11
?
Border Fault System
Basement High
Neogene Fault
(tick on downthrown side)
Monocline
Diapiric Structure
Hot Spring
Eruption Center
0
50
KM

Figure 5.

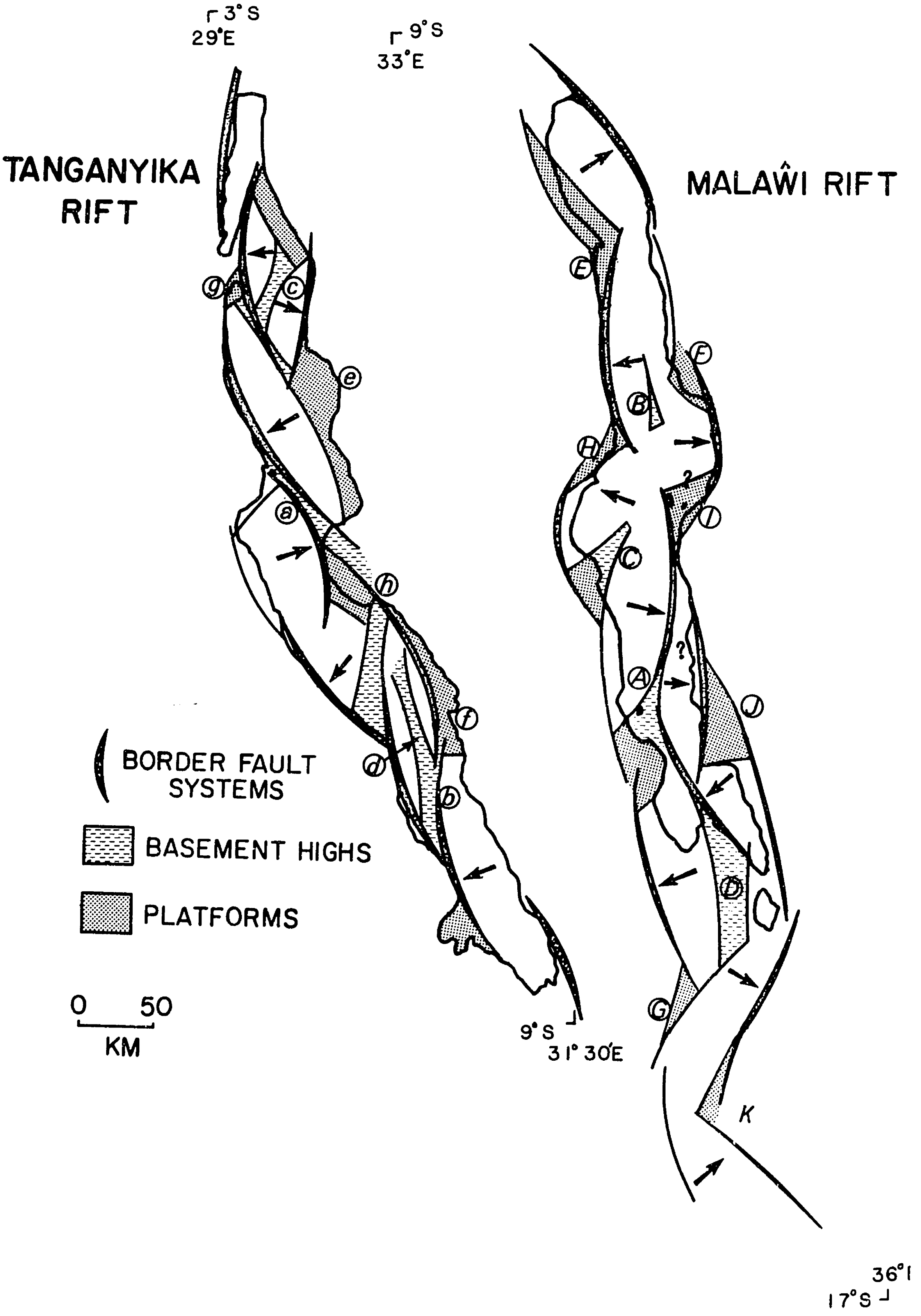
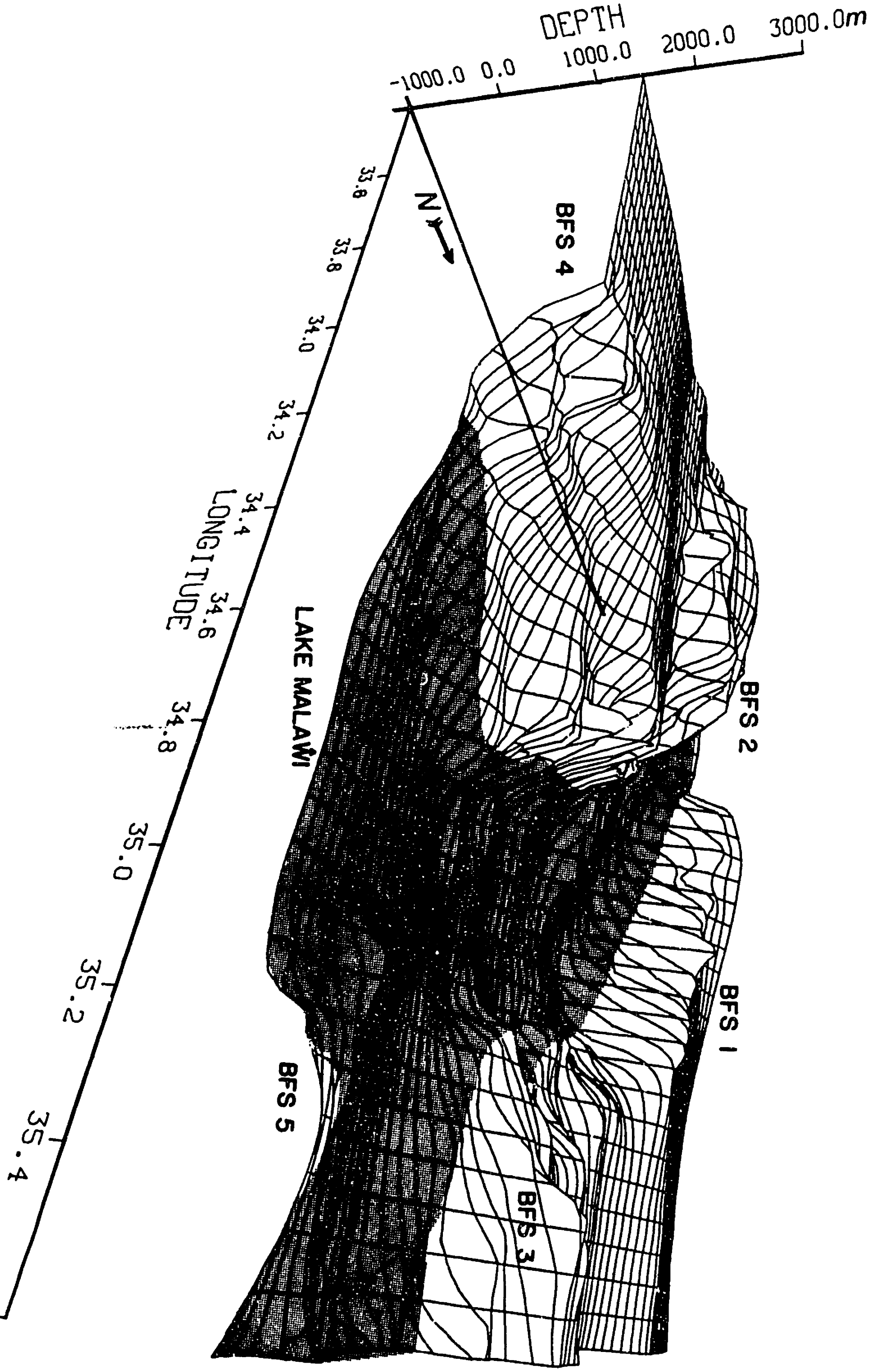

3° S
29°E
9° S
33°E
TANGANYIKA
RIFT
MALAWI RIFT
g
c
e
a
h
f
d
b
E
F
B
H
I
C
A
J
D
G
K
?
BORDER FAULT SYSTEMS
BASEMENT HIGHS
PLATFORMS
0 50
KM
9° S
31° 30'E
36°
17° S

Figure 6.

Figure 7.


DEPTH
-1000.0
0.0
1000.0
2000.0
3000.0m
N
BFS 4
BFS 2
BFS 1
BFS 3
BFS 5
LAKE MALAWI
LONGITUDE
33.6
33.8
34.0
34.2
34.4
34.6
34.8
35.0
35.2
35.4
35.6

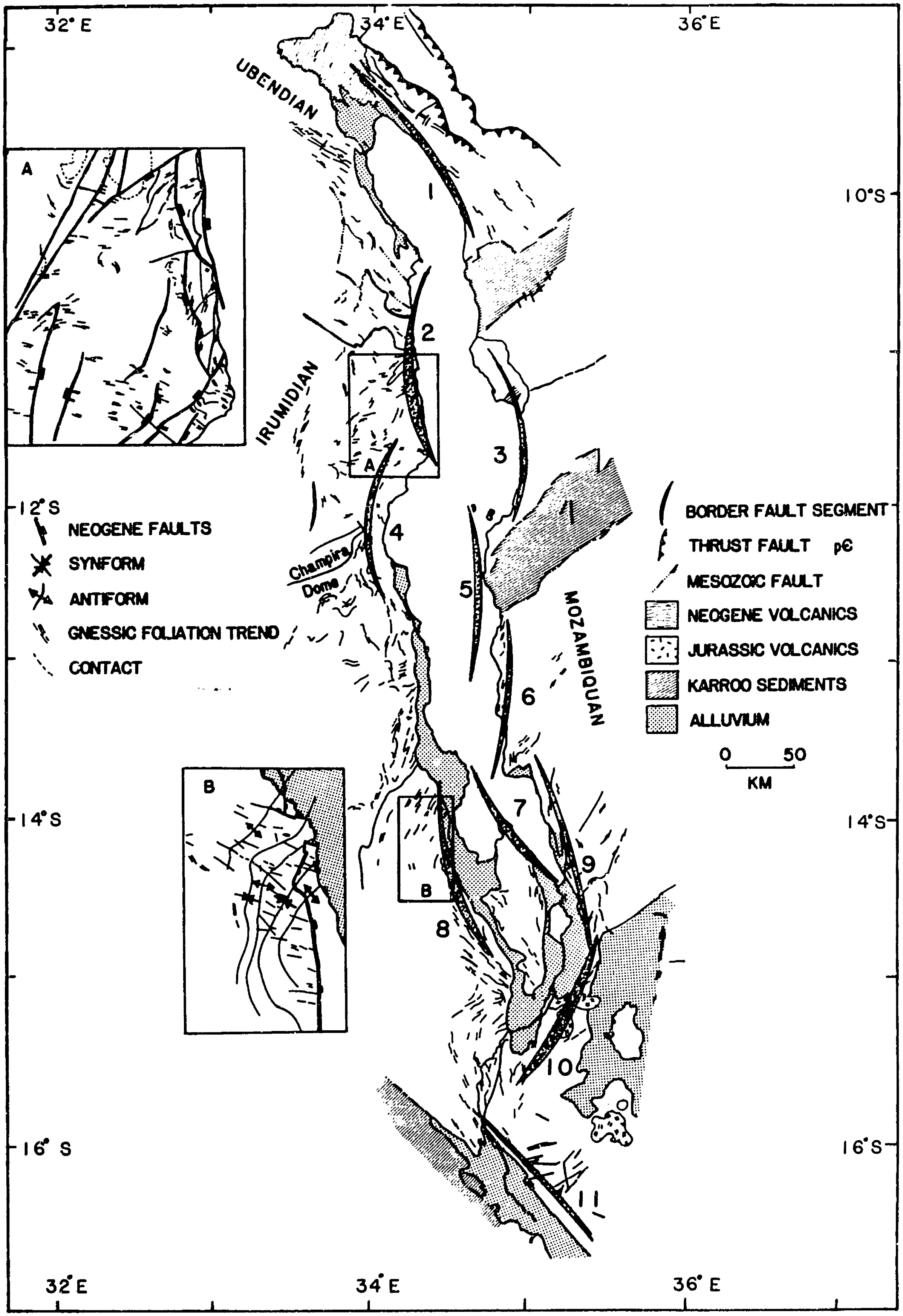

32° E
34° E
36° E
10°S
12° S
14° S
16° S
32° E
34° E
36° E
UBENDIAN
IRUMIDIAN
MOZAMBIQUAN
Champira Dome
A
B
1
2
3
4
5
6
7
8
9
10
11
NEOGENE FAULTS
SYNFORM
ANTIFORM
GNESSIC FOLIATION TREND
CONTACT
BORDER FAULT SEGMENT
THRUST FAULT pЄ
MESOZOIC FAULT
NEOGENE VOLCANICS
JURASSIC VOLCANICS
KARROO SEDIMENTS
ALLUVIUM
0 50
KM

Figure 8.

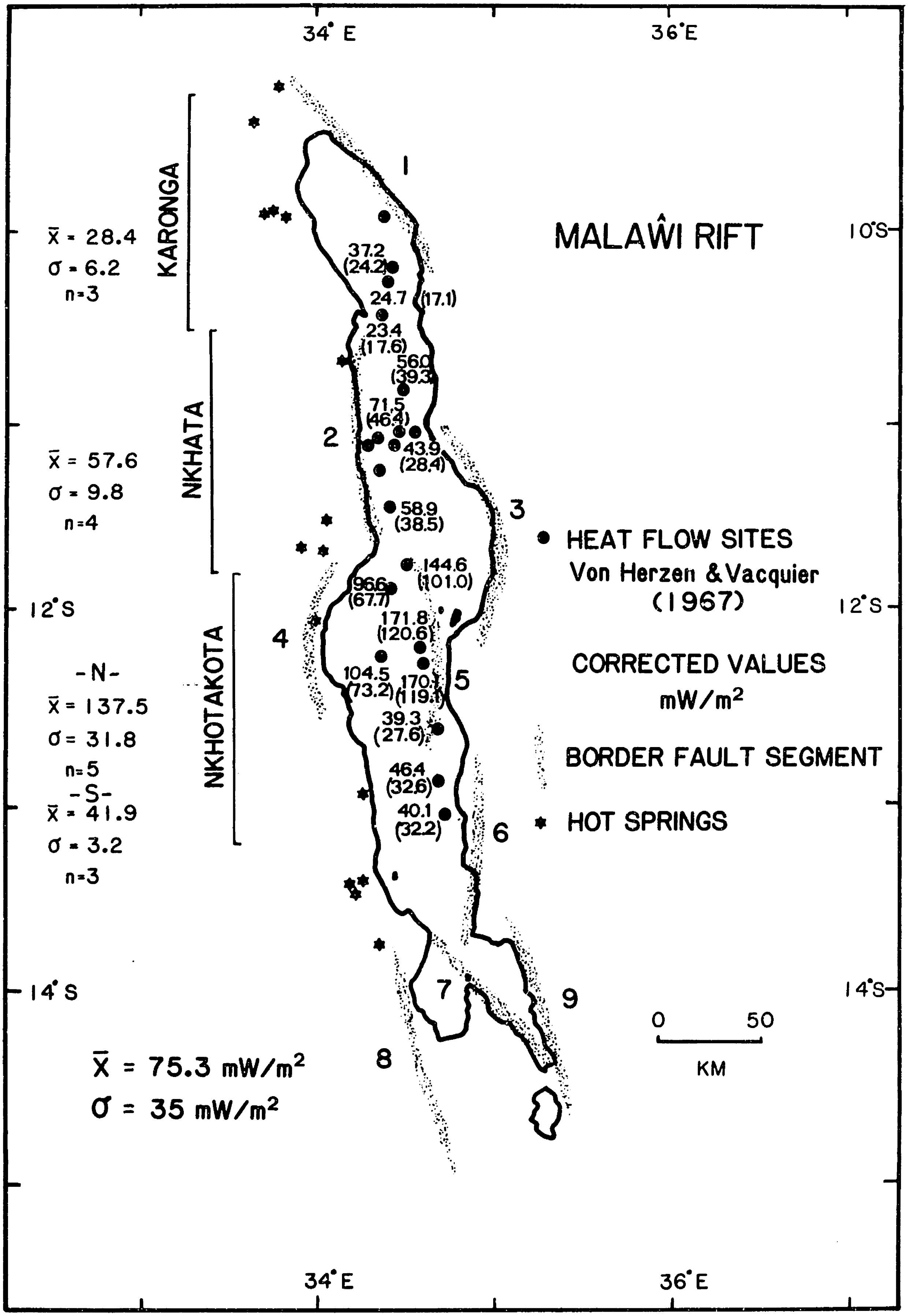

34° E
36°E
MALAWI RIFT
10°S
12°S
14°S
KARONGA
NKHATA
NKHOTAKOTA
x̄ = 28.4
σ = 6.2
n=3
x̄ = 57.6
σ = 9.8
n=4
-N-
x̄ = 137.5
σ = 31.8
n=5
-S-
x̄ = 41.9
σ = 3.2
n=3
1
2
3
4
5
6
7
8
9
37.2
(24.2)
24.7
(17.1)
23.4
(17.6)
56.0
(39.3)
71.5
(46.4)
43.9
(28.4)
58.9
(38.5)
144.6
(101.0)
96.6
(67.7)
171.8
(120.6)
104.5
(73.2)
170.1
(119.1)
39.3
(27.6)
46.4
(32.6)
40.1
(32.2)
● HEAT FLOW SITES
Von Herzen & Vacquier
(1967)
CORRECTED VALUES
mW/m²
BORDER FAULT SEGMENT
✱ HOT SPRINGS
0
50
KM
x̄ = 75.3 mW/m²
σ = 35 mW/m²

Figure 9.

Figure Captions

Figure 1. Three-dimensional models of continental rift systems. A: Orthogonal system of border faults and transfer fault systems (Lister et al., 1986). B: Curvilinear border fault segments, with linkage occurring in accommodation zones between border fault segments (after Reynolds, 1984; Bosworth, 1985). Both models make use of high-angle border fault systems that become low-angle detachments at mid-crustal levels.

Figure 2. Location of Malaŵi and Tanganyika rifts within the East African rift system (inset) showing geophysical data base used in tectonic interpretation of the Malaŵi Rift. Gravity data from Andrew (1974). Reproductions of aeromagnetic data were made available through the Malaŵi Government. Seismic line A-A' designates the location of seismic profile shown in Figure 4.

Figure 3. Lake Malaŵi bathymetry (meters below lake surface of 572m), and elevation in surrounding region. Cross-sectional profiles illustrate the alternating patterns of basinal asymmetries along the length of the Malaŵi rift. Horizontal line pattern shows sediment thickness beneath Lake Malaŵi where known. Bouguer gravity data (mgals) along southern transects from Andrew (1974). Major rivers entering and leaving Lake Malaŵi are also indicated. D = diapir.

Figure 4. Single-channel seismic reflection profile illustrating structural variations occurring along the length of the Nkhata Basin. (Location of profile A-A' shown in Figure 2). Disturbed region near end of profile interpreted as a positive "flower structure". VE ~ 16:1.

Figure 5. Compilation of Malaŵi rift structures showing locations of structural provinces referred to in text. Fault patterns mapped onshore from Stockley (1948), McKinlay (1954), James (1956), Quennell et al., (1956), Harkin (1960), Wooley and Garson (1970), Carter and Bennett (1974), Afonso, (1976), and Crossley and Crow (1980). Lake bed structures from Ebinger et al. (1984), interpretations of gravity and magnetic data. Heavier line weights denote faults with large vertical displacements. Numbers refer to border fault segments described in the text. Focal mechanism solution of 6 May, 1966 earthquake ($m_b = 5.3$) from Shudofsky (1985). Location of hot springs from Kirkpatrick (1969).

Figure 6. Stylized tectonic models of the Malaŵi rift and the Tanganyika rift (after Rosendahl et al., in press). Circled letters designate specific geometric relations described in the text. Arrows within basins point to down-dropped side of basins. "?" refer to unsurveyed regions beneath the lake.

Figure 7. Three-dimensional diagram of border fault segments 1-5 (12°S to 9°12'S; block rotated ~ 60° clockwise from North). Region filled by Lake Malaŵi shaded. Elevation in meters above and below sealevel. VE ~ 35:1.

Figure 8. Regional geology of the Malaŵi rift zone showing relationship between numbered border fault segments and Precambrian-Mesozoic structures. Geologic information from: Afonso (1976); Carter and Bennett (1973); Harkin (1960); James (1956); Quennell et al. (1956); Stockley, 1948; Wooley and Garson (1970). Ubendian, Irumidian, and Mozambiquan refer to tectonic provinces associated with Proterozoic to Precambrian orogenies that affected this region. Details of structures within regions A and B are from Hopkins (1975), and Thatcher (1968), respectively.

Figure 9. Measured heat flow values (lower number in parentheses) and values corrected for sedimentation effects within the Malaŵi rift. Measurements at unlabelled sites were made in disturbed sediments and were omitted. Mean values and standard deviations of corrected values within the four sedimentary basins bounded by border fault segments are indicated to the left of figure.

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Duke University
DURHAM
NORTH CAROLINA
27706

PROJECT PROBE
DEPARTMENT OF GEOLOGY
310 OLD CHEMISTRY

TELEPHONE (919) 684-3109
COMPUTER ROOM 684-4501
ELECTRONICS LAB 684-3941

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To Whom It May Concern:

This is to confirm that the paper entitled "Tectonic Model of the Malawi Rift, Africa" was primarily written by Ms. Ebinger. My contribution to this manuscript relates mainly to the ideas and concepts contained in Figures 1, 6, and 8. In effect Cynthia has taken a model of rifting developed by David Reynolds and myself and used it to reinterpret the tectonics of Lake Malawi. In addition to this rather passive role, I also have borne responsibility for making sure that the reinterpretation is consistent with data that we are currently collecting in Lake Malawi.

I have no difficulty whatsoever in Ms. Ebinger using this document as her Masters Thesis at MIT. Please let me know if further information is required.

Regards,

B R Rosendahl

Bruce R. Rosendahl

BRR/det