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The Bilila-Mtakataka fault in Malaŵi: An active, 100-km long, normal fault segment in thick seismogenic crust

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Abstract. Some parts of the east African rift system have deeper earthquakes (30–40 km), a larger effective elastic thickness (~35 km), and wider half grabens (~50 km) than are typical in other regions of continental extension. One such region is the southern part of the western branch of the east African rift in Malaŵi. In this region we describe a normal fault scarp that is up to 15 m high and continuous over a distance of more than 100 km. It represents the latest increment of slip, perhaps in a single earthquake, on a fault (the Bilila-Mtakataka fault) with a total offset of about 1000 m. It is the longest continuous normal fault segment that we know of on the continents, and it supports the suggestion that the thickness of the seismogenic layer is the fundamental control on the scale of geological structures that form within it. A consequence of this association is the possibility of very large (M_w 8.0), though infrequent, normal faulting earthquakes in east Africa.

Introduction

Although the east African rift system is perhaps the most famous example of continental extension on Earth, it differs in several ways from regions of extension elsewhere on the continents, such as Greece, Turkey, Nevada, and Tibet.

1. Earthquakes in parts of east Africa are deeper than in most other rifted regions. This is clear from the earthquake centroid depths, which can be determined to within about ±3 km using teleseismic *P* and *SH* waveforms, and which several authors have reported in the range 25–40 km for earthquakes in east Africa (see, e.g., *Jackson and Blenkinsop* [1993], *Seno and Saito* [1994], and *Nyblade and Langston* [1995] for summaries of this work). These deeper earthquakes occur either outside the main topographic expression of the rift system or at the southern ends of the two branches of the rift system, in Tanzania (east) and Malaŵi (west; see Figure 1a). In most other regions of continental extension, earthquake centroids are shallower than about 15 km [*Jackson and White*, 1989]. Parts of the east African lithosphere clearly have a thicker seismogenic layer than is typical elsewhere.

2. Studies of the coherence between gravity and topography have shown that parts of the east African lithosphere have an effective elastic thickness as high as 20–40 km, even within rifted areas [e.g., *Bechtel et al.*, 1987; *Ebinger et al.*, 1989]. This contrasts with smaller effective elastic thickness values of 10–15 km that are typical in other rifted areas [e.g., *Barton and Wood*, 1984; *Fowler and McKenzie*, 1989; *Bechtel et al.*, 1990].

These anomalous earthquake depths and elastic thicknesses are often attributed to the old (Archean-Proterozoic), cold, and strong material in which parts of the east African rift system are forming, in contrast to places like Greece, Nevada, and Tibet, which have undergone much younger orogenies [e.g., *Shudofsky et al.*, 1987; *Nyblade and Langston*, 1995; *Jackson and Blenkinsop*, 1993].

This paper is concerned with a possible consequence of the east African lithosphere being stronger than in other rifts; that is the associated geological structures may be bigger than usual. The normal fault systems that bound continental rifts are commonly segmented, stepping en echelon or changing the polarity of half graben along strike [e.g., *Rosendahl et al.*, 1986; *Crone and Haller*, 1991; *Roberts and Jackson*, 1991]. *Jackson and White* [1989] and *Wallace* [1989] pointed out the similarity between the maximum fault segment length of ~20–25 km common in many rifts and the downdip width of these faults in the seismogenic upper crust. (These faults typically dip at ~45° and extend to depths of ~15 km.) They suggested that the thickness of the seismogenic layer in some way influences the lateral continuity of the faults that form within it. *Jackson and White* [1989] also suggested that the effective elastic thickness of the lithosphere might be expected to con-

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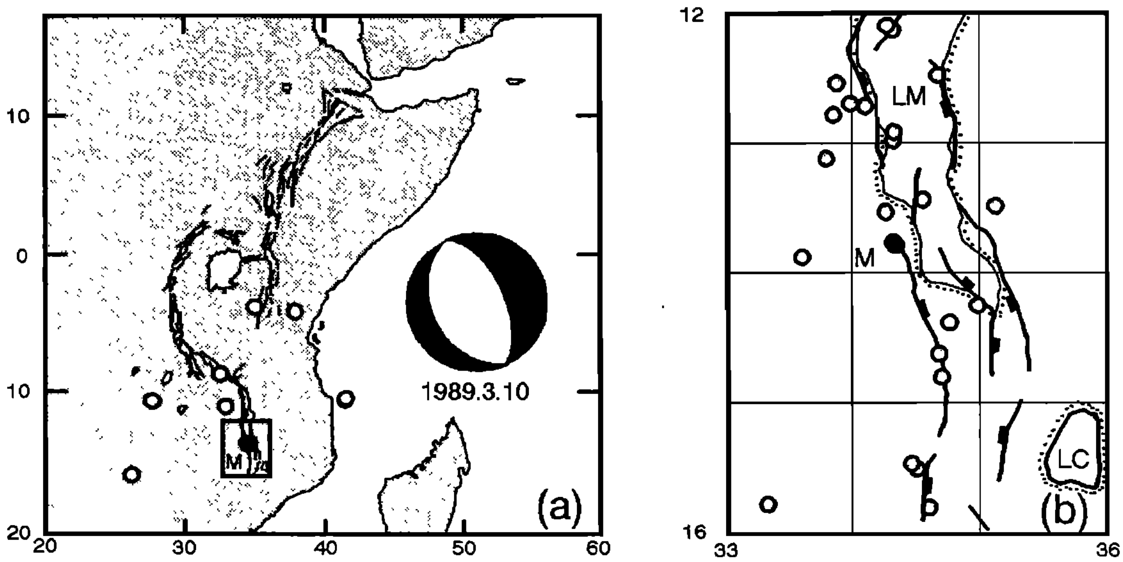

Figure 1. (a) Epicenters of earthquakes in east Africa whose centroid depths are constrained to be deeper than 20 km from analysis of body waveforms [from *Jackson and Blenkinsop*, 1993; *Nyblade and Langston* 1995; A. Foster, personal communication, 1996]. The main faults of the eastern and western rift systems are shown. The March 10, 1989, earthquake in Malaŵi is marked M. Note how these deeper earthquakes apparently occur at the southern ends of the eastern and western rifts, or off the main axes of the rifts altogether. The area of Figure 1b is marked by a box. (b) Seismicity of southern Malaŵi, from the U.S. Geological Survey Preliminary Determination of Epicenters catalogue 1963–1989. Except for the earthquakes of March 1989 (marked M), these are all small and poorly recorded: their locations may be in error by at least 25 km. LM is Lake Malaŵi and LC is Lake Chilwa.

trol the maximum width of coherently tilted blocks or half graben if the shear stresses acting on the faults are not to exceed the typical range of 1–10 MPa stress drops seen in earthquakes. There is no reason why the seismogenic thickness and the elastic thickness should have the same values, but since both are probably related to thermal structure [e.g., *Wiens and Stein*, 1983; *Burov and Diament*, 1995], we might expect them both to increase or decrease together. The hypothesis is simple: the thickness of the strong outer layer of the lithosphere might control both the lateral continuity of the faults and the across-strike width of the tilted blocks or half graben that form within it [see also *Hayward and Ebinger*, 1996].

In most regions of continental extension the thickness of the seismogenic layer varies little from 10 to 15 km, so the above hypothesis is untestable. However, parts of the east African rift system appear to be colder and stronger to greater depths than elsewhere. Are the structures correspondingly bigger?

Some of the east African half graben have widths of up to 60 km, which is far wider than the typical maximum width of ~25 km that is observed elsewhere [*Jackson and White*, 1989]. This conclusion can be reached objectively from high-quality seismic reflection data, particularly in east African lakes [e.g., *Specht and Rosendahl*, 1989; *Flannery and Rosendahl*, 1990]. *Jackson and Blenkinsop* [1993] and *Foster and Nimmo* [1996] show that such wide structures do not require abnormally high shear stresses on the bounding faults provided they are supported by an elastic layer ~30 km thick rather than the more usual 10–15 km. This aspect will not be discussed further.

Fault segment lengths are more problematic because they are harder to assess objectively, particularly from published maps. One problem is scale; faults which are drawn as continuous at one scale may appear segmented when examined in more detail [e.g., *Walsh and Watterson*, 1991; *Dawers and Anders*, 1995]. There is also a problem of definition, since most fault surfaces have irregularities in the form of corrugations and bends at all scales. A concern of this paper is fault segmentation that can potentially limit the extent of rupture and hence the size of earthquakes [e.g., *Schwartz and Sibson*, 1989]. Lateral or en echelon offsets as small as 1–2 km across strike are known to be able to halt rupture [e.g., *Lindh and Boore*, 1981; *Jackson et al.*, 1982; *Yielding*, 1985], so few seismic surveys (and none of the published ones on the African lakes) are dense enough over long enough distances to be of use to us here. It is easier to demonstrate continuity on land.

In this paper we describe the Bilila-Mtakataka fault, south of Lake Malaŵi, which we believe is a continuous fault, with no significant interruptions over a distance of at least 100 km. It is the longest continuous normal fault segment we know of on the continents. It is located about 50 km from the epicenters of earthquakes in 1989 that had centroid depths of ~32 km, where half graben widths are 40–50 km, and the effective elastic thickness is around 30 km [*Jackson and Blenkinsop*, 1993]. The fault is clearly in a region where the African lithosphere is strong.

Tectonic Setting of the Malaŵi Rift

The Malaŵi rift is located at the southern end of the western branch of the east African rift system and consists of a series of basins typically 100 km long and 50 km wide which have the morphology of half grabens that step or change polarity along strike (see *Ebinger et al.*, [1984, 1987, 1993] and Figure 2, inset). Most of the fault systems bounding these grabens are offshore or along the shore of the lake. However, at the southern end of the lake the basin-bounding faults on the west side occur entirely on land, and these faults are the subject of this study. In this region there are no rocks with an age intermediate between a metamorphic basement complex of presumed Proterozoic age and late Tertiary sediments.

The southern part of the Malaŵi rift has had few significant earthquakes in modern times (Figure 1b). The most important for this study are the two earthquakes of March 9 (M_w 5.7), and March 10 (M_w 6.1), 1989, which occurred near 13.7°S, 34.4°E, just north of the areas in Figures 2 and 3. These had centroid depths of 32 ± 5 km [*Jackson and Blenkinsop*, 1993; *Nyblade and Langston*, 1995] and produced no faulting at the surface. The larger earthquake had a well-determined normal faulting mechanism with a strike of $154 \pm 25°$ and an extension direction of $060 \pm 30°$. The total extension across this part of the rift is unlikely to exceed 10 km, and may be much less. All kinematic models of plate motions suggest maximum extension rates across the whole rift system of <3–4 mm/yr [*DeMets et al.*, 1990; *Jestin et al.*, 1994], probably decreasing to the south. Such rates, even if operative over 10 Myr, would produce extensions similar to the 16 km estimated by *Ebinger* [1989] in Kivu-Rusizi rift at the northern end of the western branch of the east African rift system.

Bilila-Mtakataka Fault

Figures 2 and 3 show the western side of the rift at the southern end of Lake Malaŵi. The regional geology of this area is described in reports and 1:100,000 scale maps by *Walshaw* [1965], *Dawson and Kirkpatrick* [1968], and *Thatcher* [1968]. Since the local geomorphology provides the best constraint on the total offset on the Bilila-Mtakataka fault and since the basement structure has a clear influence on the fault's outcrop pattern, these two aspects are discussed first before describing the fault itself in detail.

Geomorphology

In the Bilila-Mtakataka region the west side of the rift valley is bounded by two subparallel fault escarpments that separate a flat plateau with some remnant hills along the Mozambique border (elevation ~2000 m) from Lake Malaŵi (~470 m) and the Bwanje-Liwawadze valley (Figures 2 and 3). The western escarpment is not well exposed or easily accessible on the ground, as most of it is covered in forest. It is not continuous but consists of three main segments (Figure 2) (1) an unnamed scarp up to 1000 m high that runs from north of Tsekwere to the latitude of Golomoti, (2) the Chirobwe fault [*Walshaw*, 1965], forming a scarp 300–1000 m high and separated from the scarp to the north by a step to the right west of Golomoti, and (3) the Ncheu fault [*Walshaw*, 1965], forming a scarp up to 300 m high, which is offset in the north by a step to the right from the Chirobwe fault and decreases in height to the south, dying out at the Rivi Rivi river.

The eastern escarpment, bordering the Bwanje-Liwawadze valley, is the Bilila-Mtakataka Fault. Between the eastern and western escarpments lies the Nsipe-Livelezi shelf (named after the main rivers draining it to the south and north). This shelf is an almost flat erosion surface (Figure 4) that merges with the Liwawadze Valley in the south near Makenzie and with the coastal plain of Lake Malaŵi north of Mtakataka. The shelf is deeply dissected by rivers, particularly near the eastern escarpment, and is clearly the same erosion surface as that forming the Bwanje-Liwawadze Valley. According to *Lister* [1967] it may also be the same surface as that of the high plateau west of the Chirobwe and Ncheu faults. Several hills of resistant rocks rise to heights of up to about 300 m above the general level of the Nsipe-Livelezi shelf, particularly near its eastern edge (Figure 4). The shelf itself may be gently tilted to the west; *Lister* [1967] suggests by about 30 m. Though *Lister* [1967] describes the erosion surface as "African", it is of uncertain age.

The height of the Bilila-Mtakataka fault escarpment is much less than the Chirobwe-Ncheu escarpments to the west, reaching a maximum of about 500 m near the Nsipe-Livelezi divide at 14°45′S (Figures 5–8). Except at one locality discussed below, only sediments of the Bwanje-Liwawadze valley are exposed in the immediate hanging wall (i.e., the eastern side) of the Bilila-Mtakataka fault. These sediments are young, unconsolidated sands and silts, some of which may originally have been lake deposits [*Dawson and Kirkpatrick*, 1968], mixed with alluvium and reworked by surface streams. The sediments are known to be at least 50–100 m thick in places [*Walshaw*, 1965; *Dawson and Kirkpatrick*,

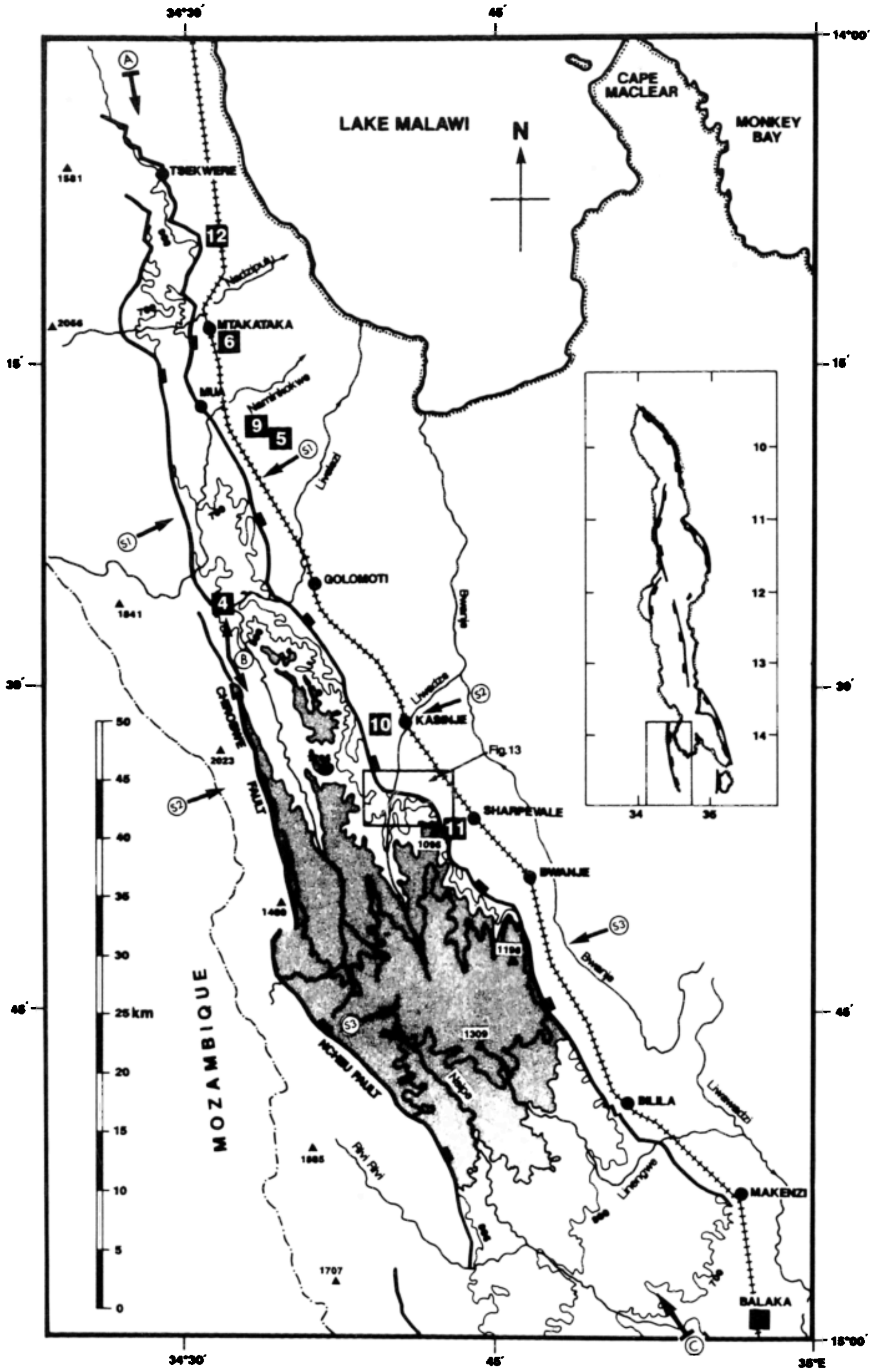

Figure 2. Summary topographic and location map of the fault system at the SW end of Lake Malaŵi. Topography is contoured at 100-m intervals and shaded above 900 m only on the Nsipe-Livelezi shelf (or erosion surface), which occupies the region between the Bilila-Mtakataka fault and the Chirobwe-Ncheu fault system. Spot heights are in meters. The railway is marked by a line with ticks. The lines of the sections S1 to S3 in Figure 7 and A-B-C in Figure 8 are also shown. The area of the air photo in Figure 13 is marked by a box. The locations of the photos in Figures 4–6 and 9–12 are shown by solid numbered boxes.

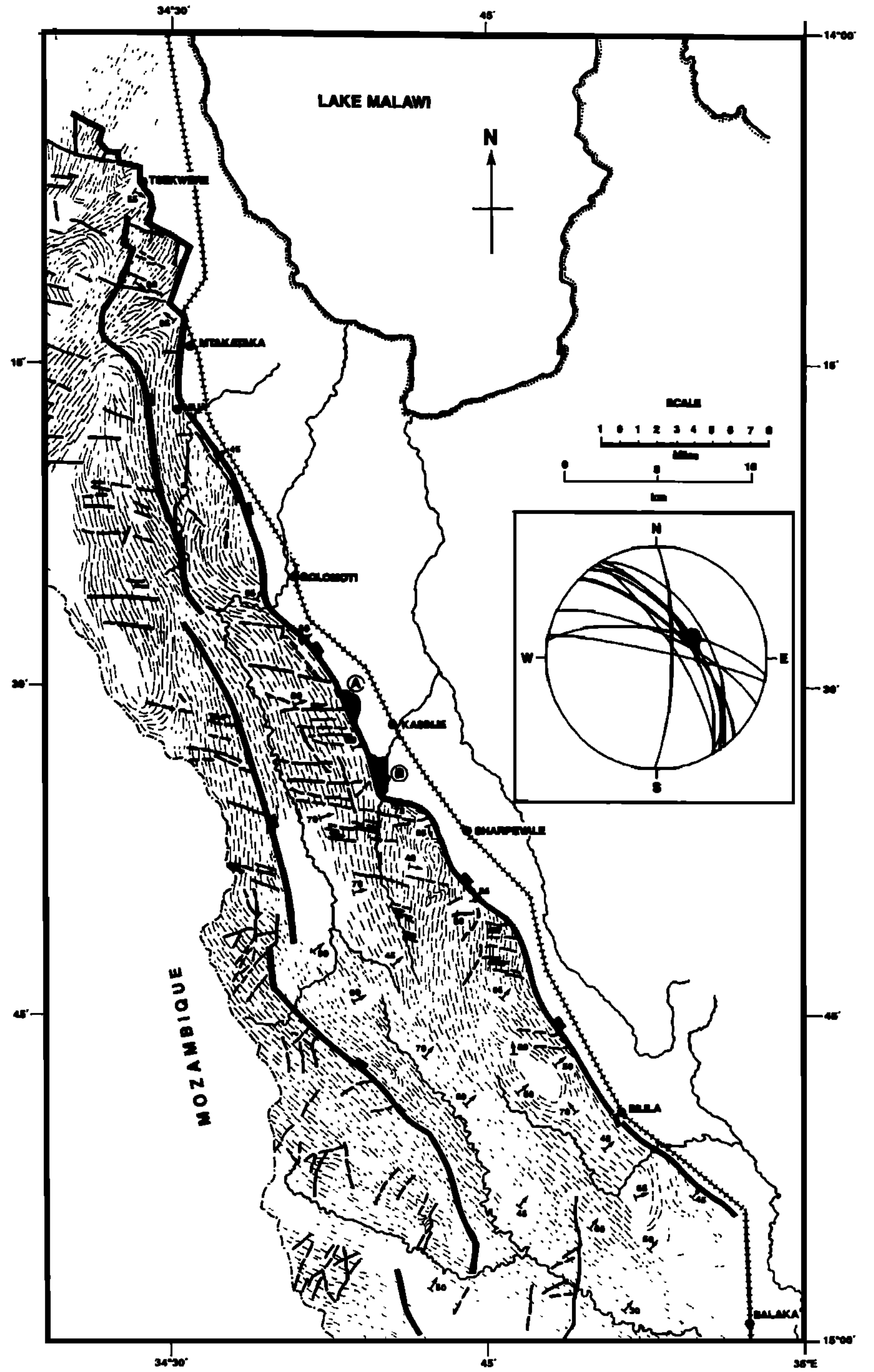

Figure 3. Structural map of the fault systems SW of Lake Malaŵi, based on work of *Walshaw* [1965], *Thatcher* [1968] and *Dawson and Kirkpatrick* [1968], as well as our own observations. Thick lines are the major faults. Medium width lines mark a less important fracture pattern generally trending WNW. Thin lines show the general trend of the foliation in the gneissic basement rocks: Arrows show representative dip values and dip directions of this foliation. The shaded areas A and B show the only two outcrops of gneiss in the immediate hanging wall of the Bilila-Mtakataka fault. Numbers in circles show the locations and directions of views in Figures 4-6 and 9-12. The inset shows a lower hemisphere equal-area projection of fracture planes found within the fault zone of the Bilila-Mtakataka scarp. A total of 11 orientations at seven different locations are shown. Also shown (open circle) is a slip vector with azimuth 060° (the same slip vector azimuth as in the March 10, 1989, earthquake) and a plunge of 60° to the ENE.

Figure 4. View south across the Nsipe-Livelezi shelf (or erosion surface) from the step at the northern end of the Chirobwe fault segment (see Figure 2 for location). The Chirobwe fault escarpment is on the right, and on the left are isolated small hills in the immediate footwall of the Bilila-Mtakataka fault.

1968] and to thin eastward, where they overlap exposed basement gneisses east of the Bwanje and Liwawadze rivers. Thus the total offset on the fault is unlikely to exceed 1000 m, and the average displacement gradient along its strike is small: ~20 m/km. This gentle gradient is one of the most striking features of the fault, which seems to have an almost constant footwall elevation over large distances (Figures 5, 6, and 9).

Figure 5. View SW of a straight part of the Bilila-Mtakataka fault between Golomoti and Mua (see Figure 2 for location). The Chirobwe fault escarpment is in the background, and the Bilila-Mtakataka fault is the escarpment separating the wooded Nsipe-Livelezi shelf from the cultivated Bwanje valley in the foreground.

Figure 6. View of the Bilila-Mtakataka fault about 1 km south of Mtakataka, looking SW (see Figure 2 for location). The Nsipe-Livelezi shelf is narrower here than in Figure 4, and this part of the fault is less straight. In the background is the escarpment of the fault segment north of the Chirobwe fault.

Basement Geology

The entire region west of the Bilila-Mtakataka escarpment consists of hornblende-biotite gneisses and charnockitic granulites interbanded with some quartzofeldspathic gneisses and calc-silicate granulites which form some of the hills and ridges on the Nsipe-Livelezi shelf. These rocks are of uncertain age but are thought to belong to the Mozambique belt and are probably Proterozoic.

Over the entire area west of the Bilila-Mtakataka fault the structure of the basement gneisses is superficially simple. A very prominent gneissic foliation has a fairly uniform strike between NW and NNW and generally dips NE at between 40° and 80° (Figure 3). In detail the structure is more complex, with local deviations in dip and strike and tight-to-isoclinal folds of the same trend that lead to repetition of some banding. The trend of the major rift-bounding faults clearly follows the general foliation in the gneisses (Figure 3) [*Walshaw*, 1965; *Dawson and Kirkpatrick*, 1968] but with some deviations from it, which are discussed below. The foliation has given a strong grain to the geomorphology on the Nsipe-Livelezi shelf, and most of the larger river courses follow it.

Another important structural fabric within the basement gneisses are fractures or joints with a WNW strike that are particularly prominent in the northern half of the area (Figure 3). This fabric is very clear on satellite imagery and influences the courses of rivers and

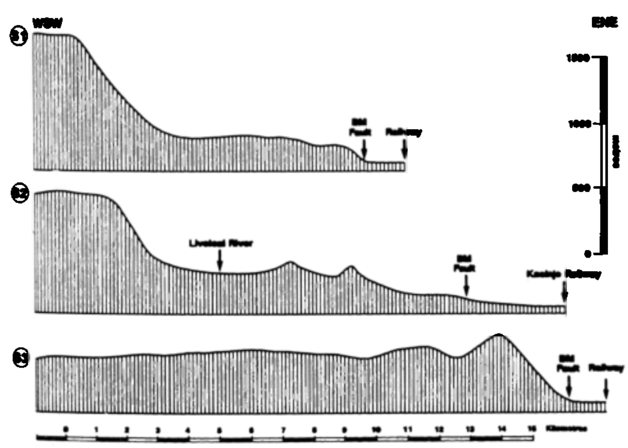

Figure 7. WSW-ENE topographic sections across the Nsipe-Livelezi shelf (see Figure 2 for location). The position of the Bilila-Mtakataka (BM) fault is marked in the east.

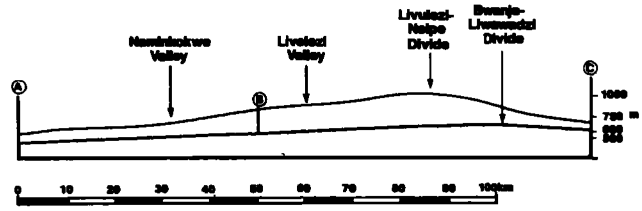

Figure 8. Longitudinal topographic section of the Nsipe-Livelezi shelf (see Figure 2 for details). The top line is the topography of the shelf. The top of the shaded area beneath is a parallel longitudinal section along the Bwanje-Liwawadzi valley.

Figure 9. View on the ground looking SW at the Bilila-Mtakataka fault scarp between Mua and Golomoti, close to the area in Figure 5 (see Figure 2 for location).

minor streams, several of which make dramatic right angle bends or zigzags as their courses switch between the directions of the foliation and the fracture fabric.

Bilila-Mtakataka Fault

The Bilila-Mtakataka fault runs from Makenzie village in the south (Figure 2) to north of the Tsekwere Estate in the north, a straight-line distance of about 110 km (Figures 2 and 3). Unlike the Chirobwe-Ncheu faults to the west, the Bilila-Mtakataka fault is well exposed, being on the edge of the cultivated Bwanje valley. A road and a railway follow the bulk of its length, and it is also accessible by the major rivers that cut through the footwall in gorges. We visited many localities on foot and flew along the entire fault at low level in a light aircraft. We also examined critical localities using air photographs.

An astonishing feature of the Bilila-Mtakataka fault, remarked on in the earlier work by *Walshaw* [1965] and *Dawson and Kirkpatrick* [1968], is the existence of a steep, clean fault scarp 4–15 m high that truncates spurs and is very clear on the ground (Figures 9–12), from the air (Figures 5 and 6), and in air photographs (Figure 13). Although no slickensides or striated surfaces are visible on this scarp (perhaps because of the granular nature of the rocks), in many places we found a strong fracture fabric, sometimes with gouge material, in the rocks forming the scarp. Its origin as a fault and as the most recent expression of movement on the Bilila-Mtakataka fault is clear. This scarp can be traced, with no significant breaks, along the entire length of the fault from Makenzie to north of Tsekwere. We will now describe its character from south to north (Figures 2 and 3). In what follows, when we refer to "the fault" we mean the Bilila-Mtakataka fault as a whole (i.e., the fault responsible for the offset of the erosion surface), and by "the scarp" we mean the clean topographic step 4–15 m high that marks the most recent movement on the fault.

The fault has a distinct southern end. Between the Linengwe River, where the scarp height is about 4 m, and Makenzie village the topography associated with both the fault and the scarp die away completely into a gentle monocline or warp that merges with the Liwawadzi valley. This is a well-known morphology at the end of a normal fault segment [e.g., *Jackson and Leeder*, 1994]. Between Makenzie and about 5 km NW of Bilila the fault more or less follows the gneissic foliation (Figure 3), and the scarp is continuous except for two minor steps at Bilila. These steps to the left are offset about 80 m and 40 m across strike, and the length of the short middle scarp linking the two long ones is less than 100 m. This disruption appears to coincide with a local change in strike of the gneissic foliation from about 140° in the south to 170° in the north. The scarp height does not change observably while crossing these steps, and the whole disruption is obviously of only minor significance: yet this is the biggest discontinuity in the scarp we could detect over its entire length.

Between about 5 km north of Bilila and the Liwadze River the fault cuts across the complicated pattern of

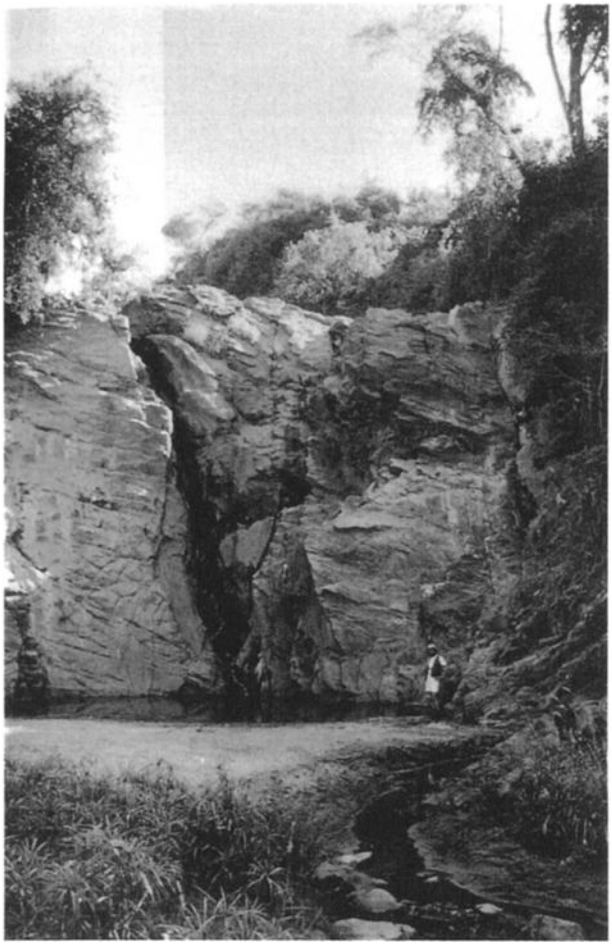

Figure 10. View west of a waterfall on the Bilila-Mtakataka scarp west of Kasinje (see Figure 2 for location). The waterfall has retreated about 50 m upstream from the line of the scarp and is formed in foliated gneiss. T. Blenkinsop, of height 1.70 m, provides the scale.

foliations in the basement rocks. Its outcrop is much less straight and some of the curves in its trace are severe, as it changes strike from NNW to WNW in places. Yet throughout this region the scarp itself is continuous (e.g., Figure 13). West of Sharpevale (Figure 3), in a place where the scarp is exposed by burning of vegetation and is about 8 m high, a clear stream terrace is preserved by uplift in the footwall (Figure 11). Here the scarp itself is a very steep free face that was preserved from erosion by vegetation but is now degrading. It contains a strong fracture fabric parallel to the scarp in brecciated gneiss but no slickensides.

Between Sharpevale and the Liwadze River the fault changes strike to WNW as it crosses the foliation in calc-silicate gneisses. In this region it may be following the WNW trending fracture pattern that is prominent in the basement rocks (Figure 3). At the Liwadze River itself the fault changes strike abruptly from WNW to NNW. It then continues north as an almost straight line, closely following the basement foliation once again. These changes in strike between Sharpevale and north of the Liwadze River crossing are the most dramatic seen along the fault, yet the clean scarp is continuous round them all (Figure 13). In the corner by the Liwadze River crossing, and for the next 8 km north, are the only exposures of basement gneiss in the hanging wall of the fault (marked A and B in Figure 3). We are uncertain how to interpret these. These outcrops may imply a smaller total offset on the fault at this point (though the youngest scarp itself does not change height significantly in this region). Alternatively, they may be remnants of high topography in the erosion surface of the Nsipe-Livelezi shelf, which is studded with minor hills, particularly in this region.

From Kasinje to Mua the fault is relatively straight, following the gneissic foliation most of the way (Figure 5). It makes a minor bend where it crosses the Livelezi River, but the scarp is identifiable on both sides and has caused a single terrace to be preserved in the uplifted footwall on the south side at a height of about 10 m. Above the terrace is a more subdued riser also ~10 m high that becomes a flat shelf in the gneiss about 100 m wide before rising again up to the higher erosion surface. This morphology is a common feature of the fault: we observed it at several localities, particularly at Bwanje and south of Mua, and it is remarked on by *Walshaw* [1965] and *Dawson and Kirkpatrick* [1968]. Their suggestion, which we think reasonable, is that this higher bench in the gneiss represents a slip event prior to the one (or ones) that produced the current free scarp face.

At Mua mission itself the scarp is about 10–12 m high and exposes unconsolidated sediments overlying weathered basement gneiss in the footwall [*Dawson and Kirkpatrick*, 1968]. These deposits appear to have formed in a channel and may represent a terrace in the nearby Myendoparive River. From Mua northward the fault makes a series of straight zigzags as it alternates between following the WNW fracture fabric and the NNE gneissic foliation. The scarp is continuous round all these changes in direction, maintaining its height at about 8–10 m. At 8 km north of Mtakataka it turns abruptly WNW toward Tsekwere, and on this corner, valley floor sediments are seen in the footwall above the gneiss (Figure 12).

We were able to follow the scarp (from the air) another 2 km NW of Tsekwere, where a farm is built on an uplifted river terrace. Beyond that the fault is not clear: the region is thickly forested, and the Nsipe-Livelezi shelf is no longer identifiable in the footwall because the high western escarpment that marks the fault segment north of the Chirobwe fault in some way meets, interferes, or merges with the NW trend of the fault through Tsekwere. We could not confirm *Walshaw*'s

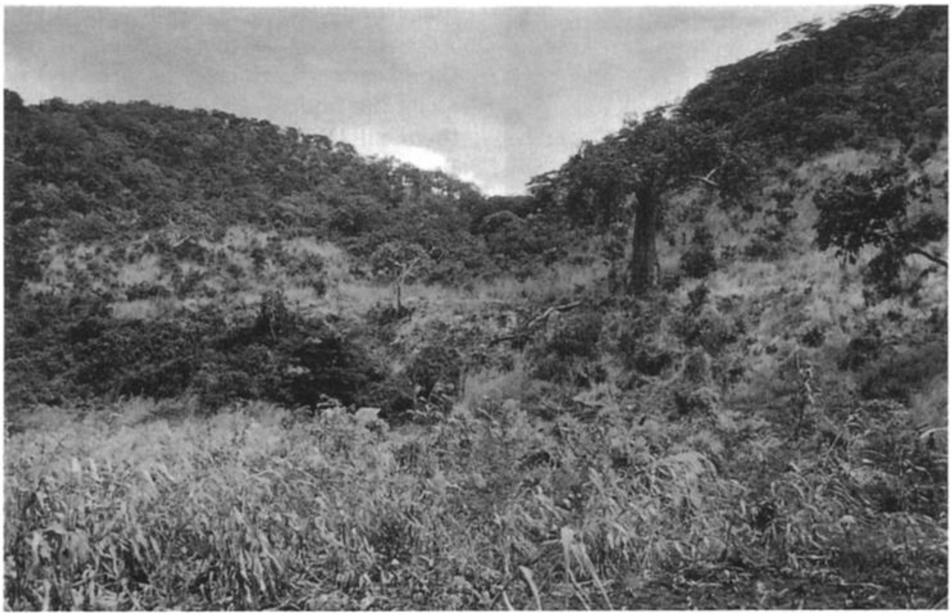

Figure 11. View west of the steep scarp on the Bilila-Mtakataka fault west of Sharpevale (see Figure 2 for location). The flat surface is a river terrace offset about 8 m above the valley floor. The scarp has recently been exposed by burning.

[1968] suggestion that the Bilila-Mtakataka fault continues 30–40 km farther north of Tsekwere to Salima.

Some feeling for the youth of the scarp itself may be obtained where it crosses rivers. West of Kasinje (Figure 2) is a waterfall ~15 m high (Figure 10) that has retreated upstream about 50 m from the place where the scarp crosses this moderate-sized stream. This rather small distance is typical of the amount of scarp retreat, even on bigger streams crossing the fault south of Mua (the Naminkokwe) and Tsekwere (the Ngodzi). On the

Figure 12. The Bilila-Mtakataka scarp 8 km north of Mtakataka (see Figure 2 for location) where it turns abruptly WNW toward Tsekwere. This view is to the WNW just south of the turn. The scarp is about 8 m high and here has soft valley sediments in the uplifted footwall, which has eroded and gullied more than is common where only gneiss is exposed. However, the sediment cover in the footwall is only a few meters thick.

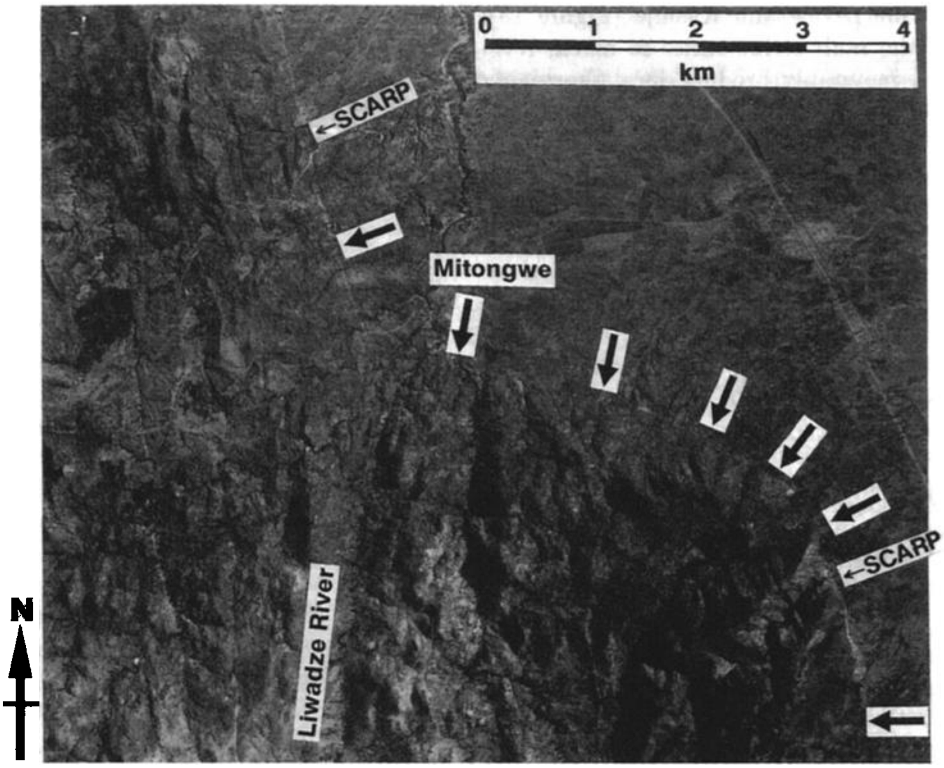

Figure 13. Air photograph of the big bend in the Bilila-Mtakataka fault and scarp where it turns from a WNW strike west of Sharpevale to a NNW scarp west of Kasinje as it crosses the Liwadze River (see Figure 2 for location). The scarp itself is the clear white line.

much bigger Livelezi River west of Golomoti the nick point caused by the scarp is now an area of rapids about 100 m upstream. The discharge from these rivers in the wet season is considerable, and the fact that the nick points are still identifiable close to the scarp suggests to us that the motion on the scarp is not very old, but we cannot quantify this.

Unresolved Issues

There are various aspects of the Bilila-Mtakataka fault that we do not understand and which we identify below. However, first we wish to emphasize the most important feature that we do understand and which is the point of this paper: that the frontal scarp, which marks the most recent episode of movement on this fault, is continuous for at least 100 km from Makenzie in the south to Tsekwere in the north. This is in spite of the various bends and zigzags in the fault trace, whose outcrop is clearly influenced by preexisting basement foliation or fracture trends. The only discontinuities we could find were the obviously minor and unimportant steps at Bilila, which anyway are only 12 km from the southern end of the fault.

The most obvious uncertainty is the age of the movement represented by the frontal scarp. The observations that (1) soft valley floor sediments (north of Mtakataka and at Mua) and uplifted river terraces are preserved in its footwall, (2) nickpoints in moderate-sized rivers have not migrated far upstream, and (3) the scarp face is still very steep suggest that the movement is relatively young, but we cannot confidently quantify this statement. If the scarp moved 10 m in one slip event (see below) and if the long-term slip rate were 1 mm/yr (improbably high, since there are other faults at this latitude), such an event would only be required every 10,000 years.

What is the slip vector on the fault? We were unable to find slickensides or striations in the brecciated fault zone on the scarp. *Chorowicz and Sorlien* [1992, Figure 2] indicate a NW-SE extension direction on this fault, suggesting almost pure strike-slip motion. Their measurements of striations were made "on surfaces parallel to and within 100 m of the major fault" (page 1019). We cannot comment on whether their measurements record the same age of deformation as the most recent slip on the fault. However, a substantial strike-slip component, or NW-SE extension direction, seems unlikely to us for three reasons. First, the motion on the scarp is obviously mainly vertical or dip slip. We were unable to detect any convincing strike-slip offsets, either on the ground or from the air (both aeroplane and air photos). This was true even when the strike of the fault changes dramatically, as it does between Sharpevale and Kasinje (Figure 13). Second, because the fault strike varies so much, NW-SE motion would inevitably produce local shortening in some places that would at the very least change the nature of the vertical displacement on the scarp. We saw no evidence of this anywhere. Third, the March 10, 1989, earthquake, only 40 km north of Tsekwere, has a well-determined slip vector in the direction $060 \pm 30°$, quite different from the NW-SE direction suggested by *Chorowicz and Sorlien* [1992]. A slip vector in this direction would produce almost pure normal faulting on the Bilila-Mtakataka fault. A plot of the fracture planes we found in the faulted rocks of the scarp itself is shown in Figure 3, inset. Most of these planes could have a common slip vector with an azimuth close to that of the March 10, 1989, earthquake (060°, plunging at 60°) without requiring much internal deformation of the footwall or hanging wall.

Does the continuous scarp along the fault represent slip in a single large earthquake? From the observational point of view we saw no evidence for several slip events producing the steep frontal scarp. Where we saw uplifted river terraces or waterfalls, we saw a single riser the height of the whole scarp: there were no signs of multiple steps within the frontal scarp. However, these observations may not be conclusive if, for example, several earthquakes happened close together in time. If the scarp were produced in a single event, with an average slip of ~10 m over 100 km length, it would be the biggest normal faulting earthquake known on the continents. For comparison, two of the largest continental normal faulting earthquakes this century are (1) the 1959 Hebgen Lake, Montana, earthquake (total fault length ~40 km; average slip ~6 m; $M_0 \sim 10^{20}$ N m; M_w 7.3 [*Myers and Hamilton*, 1964]) and (2) the 1915 Pleasant Valley, Nevada, earthquake (total fault length ~60 km; average slip ~3-4 m; $M_0 \sim 0.7 \times 10^{20}$ N m; M_w 7.2 [*Wallace*, 1984]). In both of these earthquakes the surface faulting occurred in discrete segments that probably moved in discrete subevents identifiable in the seismograms [*Doser* 1985, 1986]. By contrast, a single slip event on the Bilila-Mtakataka fault, with average displacement of 10 m over 100 km extending to 40 km depth, would have a moment of $\sim 10^{21}$ N m (M_w 8.0). Such a large earthquake with a large slip increment is a straightforward consequence of the increased fault length and seismogenic depth (which increases the fault area). Nonetheless, we know of no normal faulting events of this size on the continents this century, and the historical record in Africa itself is too short to be of use [*Ambraseys and Adams*, 1991]. A reasonable analogue for such an event may be the big normal faulting earthquakes seaward of trenches in subduction zones, which can even exceed this in size, such as the 1933 Sanriku (M_w 8.4) and 1977 Sumbawa (M_w 8.2) earthquakes [*Kikuchi and Kanamori*, 1995]. These events achieve their great size by rupturing oceanic lithosphere to depths of 40 km or more [e.g., *Chapple and Forsyth*, 1979; *Wiens and Stein*, 1983].

Discussion

Our work in Malaŵi set out to discover whether there was any evidence for continuous fault segments substantially longer than about 25 km in regions where anomalously deep normal faulting earthquakes occur. This question has been answered by the Bilila-Mtakataka scarp, which is certainly continuous for at least 100 km (as, indeed, was pointed out by *Walshaw* [1965] and *Dawson and Kirkpatrick* [1968]). Since this scarp obviously represents the most recent increment of motion on the fault and is traceable along its entire length, our conclusion regarding its continuity is not subjective. This is lucky for us, as it is sometimes difficult to be objective with arguments based on morphology or structure alone. For our purposes, we can bypass difficult questions about the origin and evolution of the fault. For example, the dramatic bend in the fault at the Liwadze River west of Sharpevale, with the exposed gneiss in the hanging wall, is similar to the geometry expected when two en echelon faults merge along strike by breaking the "relay ramp" between them [e.g., *Trudgill and Cartwright*, 1995]. Thus the fault may have originated as two segments that joined together. This does not matter for us as the (remarkable) fact that the scarp is continuous through this region demonstrates that now it behaves as a single fault.

The Bilila-Mtakataka fault thus supports the notion that the thicker seismogenic crust in this region is associated with longer normal faults as well as with wider half grabens and greater elastic thickness [*Jackson and Blenkinsop*, 1993] and that the thickness of the seismogenic layer may be the fundamental control on the scale of geological structures in the crust [*Jackson and White*, 1989; *Wallace*, 1989]. A consequence of this association is the probability of very large, but infrequent, normal faulting earthquakes in parts of east Africa. However, it is clear that one example does not prove the general point. Other areas with thick seismogenic crust in Africa and elsewhere need to be examined. One such region is around Lake Baikal, which may also have a large elastic thickness [*Diament and Kogan*, 1990] and earthquakes as deep as 40 km [*Déverchère et al.*, 1991].

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