

1 **Controls on early-rift geometry: new perspectives from**
2 **the Bilila-Mtakataka fault, Malawi**

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7 **Key Points:**

- 8 • = The segmented 110 km long Bilila-Mtakataka fault scarp is oriented oblique to
9 the current regional extension direction =
- 10 • = The surface expression is compatible with the upward propagation of a buried
11 weak zone that fits the local stress field =
- 12 • = High-grade metamorphic foliation locally influences scarp trend at the surface
13 =

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Abstract

We use the ~ 110 km long Bilila-Mtakataka fault in the amagmatic southern East African Rift, Malawi, to investigate the controls on early-rift geometry at the scale of a major border fault. Morphological variations along the 14 ± 8 m high scarp define six 10-40 km long segments, which are either foliation parallel, or oblique to both foliation and the current regional extension direction. As the scarp is neither consistently parallel to foliation, nor well oriented for the current regional extension direction, we suggest the segmented surface expression is related to the local reactivation of well oriented weak shallow fabrics above a broadly continuous structure at depth. Using a geometrical model, the geometry of the best-fitting subsurface structure is consistent with the local strain field from recent seismicity. In conclusion, within this early-rift, pre-existing weaknesses only locally control border fault geometry at subsurface.

1 Introduction

Rift structure is controlled by the geometry of border faults. In intact, isotropic rocks, normal border faults would strike perpendicular to the least principal stress and dip 60° . Frictionally weak and/or low cohesive strength caused by pre-existing structures can, however, localize strain and provide surfaces for fault reactivation [e.g. *Bellahsen et al.*, 2013; *Walker et al.*, 2015; *Worthington and Walsh*, 2016], including structures that are not ideally oriented in the current stress field [e.g. *Ebinger et al.*, 1987]. Therefore, pre-existing structures formed in both current and previous deformation phases can have a fundamental influence on rift geometry [e.g. *Whipp et al.*, 2014; *Phillips et al.*, 2016]. For young rifts where the initial structure is currently being established, such as parts of the East African Rift System [*Macgregor*, 2015b], pre-rift structures such as basement foliations, or structures originating from older rift events, have been suggested as primary controls on the current rift geometry and evolution [*Corti*, 2009; *Morley*, 2010; *Delvaux et al.*, 2012]. However, alternative hypotheses suggest that early rifting is controlled by the stress field at the time of fault nucleation [*McClay and Khalil*, 1998; *Fazlikhani et al.*, 2017], anisotropy in the lithospheric mantle [*Tommasi and Vauchez*, 2001] or thermal weakening [*Claringbould et al.*, 2017].

As well as rift-scale observations, the influence of pre-existing structures has been demonstrated in laboratory rock deformation [e.g. *Collettini et al.*, 2009] and analogue experiments [e.g. *Bellahsen and Daniel*, 2005]; yet, over the scale of an individual fault their influence is less clear [e.g. *Whipp et al.*, 2014; *Phillips et al.*, 2016]. An expectation is that a major fault is either parallel to reactivated weak surfaces, or in an orientation consistent with fault nucleation in the current stress field. In the Suez Rift, a combination of these options is illustrated by foliation-oblique faults reflecting the stress at fault initiation, hard-linked by foliation-parallel faults [*McClay and Khalil*, 1998].

Here we address the relative importance of the controls on rift and fault geometry, by using high-resolution satellite and field measurements to describe the geometry of the Bilila-Mtakataka fault (BMF) and foliations in the crystalline footwall rocks (Fig. 1a). The BMF is a normal border fault at the southern end of the amagmatic Malawi Rift System (MRS), whose surface trace has been suggested to comprise a continuous ~ 10 m high scarp for ~ 100 km [*Jackson and Blenkinsop*, 1997]. Rift initiation in the southern MRS may be as recent as early to middle Pliocene [*Lyons et al.*, 2011], so the BMF provides a rare natural laboratory for the relationship between basement foliation and fault geometry in the early stages of rifting. We discuss whether BMF geometry is consistent with basement reactivation, stresses inferred from regional extension, and/or a different local stress field at the time of initiation. With the availability of this dataset, we also aim to provide new insights into the morphology of one of the Earth's longest, continental normal fault scarps.

2 Data Collection and Methodology

We analyse a 12 m resolution TanDEM-X digital elevation model (DEM) using QGIS to calculate scarp height and width from elevation profiles along the BMF scarp at 1 km intervals (Fig. 1c). The BMF scarp was mapped at 1:100 scale from 14.04°S, 34.34°E to 14.93°S, 34.94°E; 128 profiles were extracted, each with a length of 400 m. As the slip direction is considered to be pure normal [Jackson and Blenkinsop, 1997; Chorowicz and Sorlien, 1992], elevation profiles were oriented perpendicular to the local scarp trend. Previous regional fault studies in Malawi have used a 30 m SRTM DEM to map faults [e.g. Laó-Dávila et al., 2015]; however, TanDEM-X is higher-resolution and has higher absolute and relative vertical accuracies [e.g. Gruber et al., 2012]. Here, for a subsample of 50 control points, the median difference between the TanDEM-X DEM and an SRTM DEM was found to be less than 5 m.

Scarp height is defined as the elevation difference between regression lines fitted to the footwall and hanging wall surfaces, extrapolated to a line through the point of maximum slope on the fault scarp [Fig. 1c; Avouac, 1993]. To generate the regression lines, the bottom and top of the scarp were picked manually. Measurements were repeated three times in random order to calculate uncertainty. Interpretation of each profile can be found in the supporting information. The root mean square error (RMSE) for the regression lines was on average ~ 1.5 m (Table S2) and the standard deviation of errors between measurements was ~ 0.4 m (red circles, Fig. 2b). Measurement repeatability (here defined as horizontal error between all scarp-picks of less than 10 m) was achieved for 102 of the 128 profiles (blue circles, Fig. 2b), with fewer repeatable measurements at the ends of the fault where the scarp is smaller and therefore more difficult to recognise in the DEM (Fig. 2b). To reduce measurement errors or other local site effects [e.g. erosion, Zielke et al., 2015], a 5 km moving average and standard deviation are applied to the repeatable measurements (blue line and envelope, Fig. 2b).

In the field, the scarp is expressed as a soil-mantled hillslope. Bedrock exposures are scattered, and there are no known exposures where displacement can be directly measured across the fault. No fault plane slip direction indicators unequivocally formed by rift-related faulting were found. Dip and dip azimuth of the scarp slope were measured at seventeen locations (Fig. 2e), but note that given the weathered, soil-dominated nature of the scarp, the dip is representative of the angle of repose and may be less than the dip of the fault plane. Thus, whereas the uncertainty in the absolute dip measurements is $\sim 5^\circ$, this dip may differ significantly from fault plane dip. Basement foliation orientation was also measured in the footwall amphibolite to granulite facies gneisses at each location and augmented by interpolation of composition and fabric orientations from geological maps [Fig. 1b, Walshaw, 1965; Dawson and Kirkpatrick, 1968]. The mineralogy of the gneisses is dominated by biotite, feldspar and quartz in variable modal proportions, with smaller but variable modes of hornblende and garnet. The gneissic foliation is continuous, cohesive, and typically planar, but locally anastomosing, and defined by both mineral segregation banding and preferred mineral orientations.

3 Results

3.1 Scarp Morphology and Segmentation

Analysis of the TanDEM-X DEM shows that the trend of the BMF scarp is locally variable, with an average of $\sim 150^\circ$ (Fig. 2a). This average trend is at an angle of 64° to the current regional plate motion vector estimate of $086^\circ \pm 5^\circ$ [Saria et al., 2014, Fig. 2d]. On the other hand, this average scarp trend is 88° to a local, minimum horizontal stress (Sh_{min}) inferred from 13 earthquake focal mechanisms in the Malawi rift [Delvaux and Barth, 2010, Fig. 2d]. The footwall basement foliation has a bimodal strike distribution with peaks at 160° and 205° , but varies considerably along the BMF (Fig. 2a).

114 The average scarp height is 14 m ($\sigma = 8$ m) but varies by an average of 6 m per
 115 km; the largest measured scarp height is ~ 34 m (Fig. 2b). Only minor changes in scarp
 116 morphology occur at major rivers. The scarp height displays two bell-shaped, near-symmetrical
 117 profiles; one in the north (0~80 km) and one in the south (95~128 km). Between 80 and
 118 95 km, scarp height is almost zero and the scarp trend varies considerably, forming two
 119 bends around surface exposures of calc-silicate granulite (Fig. 1b, 2c). Based on major
 120 gaps in fault scarp continuity or distinct along-strike changes in scarp morphology and/or
 121 scarp trend [e.g. *Crone and Haller, 1991*], the BMF can be divided into six segments (Fig.
 122 2; Table S1). These segments are now described from north to south.

123 3.2 Structural Analysis of BMF Segments

124 In the northernmost segment, Ngodzi, the fault scarp orientation alternates in a
 125 zig-zag pattern between a predominant trend of 110° , which crosscuts gneissic foliations,
 126 and a foliation-parallel trend of 210° , where the scarp is steepest. For the northernmost
 127 few kilometres, a scarp is not obvious on the DEM profiles, but then a scarp of 13 ± 8 m
 128 can be traced (Fig. 2b).

129 Along the Mtakataka segment an 18 ± 5 m high scarp is sub-parallel to the eastward-
 130 dipping foliation (dip $48^\circ \pm 22^\circ$, Fig. 2e), except at the river Nadzipulu where the scarp
 131 (locally 25 m high) crosscuts the foliation to trend $\sim 120^\circ$ for two kilometres. As in the
 132 Ngodzi segment, the scarp dips more gently ($\sim 30^\circ$) where the scarp and foliation are
 133 sub-parallel, than where the scarp crosscuts the foliation ($\sim 40^\circ$, Fig. 2e).

134 The Mua segment is convex in shape, consistently oblique to the foliation, and its
 135 trend rotates south-westward from 150° to 200° at 2° per km (Fig. 2a). Scarp height
 136 is 20 ± 6 m and decreases slightly at both ends of the segment (Fig. 2b). Toward the north-
 137 ern end, at the Naminkokwe river, a 13 m high knickpoint has eroded back 70 m; and
 138 a number of steeply dipping extensional fractures, likely associated with recent fault-related
 139 deformation, strike parallel to the scarp and cross-cut the gently dipping foliation (Fig.
 140 3a-c). The Mua segment intersects the Kasinje segment at the river Livelezi, where the
 141 scarp abruptly rotates from trending 185° to a trend of 115° (Fig. 2a). This change co-
 142 incides with an increase in scarp dip to 45° (Fig. 2e).

143 In contrast to the Mua segment, the entire Kasinje segment is parallel to foliation
 144 that dips eastward at $53^\circ \pm 9^\circ$ (Fig. 2a,e). The scarp is concave in map view, and scarp
 145 trend and foliation strike both increase southward by around 2° per km. The scarp is
 146 clearly defined with an average height of 16 ± 8 m, reaching a maximum of 24 m near the
 147 segment centre. A 16 m high knickpoint in the Mtuta river is set back 40 m from the
 148 scarp front, and shows that the fault is parallel to the local foliation and lacks a frac-
 149 tured footwall damage zone (Fig. 3d-f). Scarp height decreases to less than 10 m sev-
 150 eral kilometres from the intersection with the Citsulo segment.

151 The Citsulo segment has an irregular scarp trend that alternates between $\sim 120^\circ$
 152 and $\sim 185^\circ$. The scarp trace forms two large, approximately right angle bends (Fig. 1a).
 153 In the field, the scarp can be traced around both bends; however, it is difficult to iden-
 154 tify the fault scarp from the hills behind it between these features. Although two < 10
 155 m high north-south trending scarps can be identified in the DEM, they are offset by sev-
 156 eral kilometres (Fig. 2b). This is the only discontinuity of the scarp trace along the en-
 157 tire surface length of the BMF, and we define this as the ‘Citsulo discontinuity’. The foot-
 158 wall lithology is more variable here than elsewhere along the fault, and comprises inter-
 159 calated bands of felsic orthogneisses, mafic paragneisses and calc-silicate granulite (Fig.
 160 2c), with a steeply dipping ($62^\circ \pm 13^\circ$), variably folded and locally discontinuous folia-
 161 tion.

162 The southernmost segment, Bilila, has a concave scarp parallel to strike of folia-
 163 tions that dip eastward at $53^\circ \pm 19^\circ$. A scarp of height 9 ± 6 m can be seen along the en-

164 tire segment before the scarp becomes indistinguishable on the DEM after 120 km. Lithol-
 165 ogy along the Bilila segment varies between a volumetrically dominant mafic paragneiss
 166 unit, and bands of calc-silicate granulite and felsic paragneisses.

167 4 Discussion

168 4.1 Variations in scarp trend

169 The total length of the surface fault trace where a scarp was identified in the DEM
 170 is ~ 110 km. The along-strike profile of scarp height displays two bell-shaped profiles,
 171 and comprises several peaks and troughs indicative of fault segmentation [e.g. *Crider and*
 172 *Pollard*, 1998; *Crone and Haller*, 1991; *Walker et al.*, 2015, Fig. 2b]. Segmented, but bell-
 173 shaped scarp height profiles generally result from hard-links between initially indepen-
 174 dent segments [e.g. *Trudgill and Cartwright*, 1994; *Anders and Schlische*, 1994; *Dawers*
 175 *and Anders*, 1995], and/or interactions with other structures or strength anisotropies [e.g.
 176 *Fossen and Rotevatn*, 2016]. An increase in scarp dip at intersegment zones along the
 177 fault (e.g. between the Mua and Kasinje segments) may also be due to hard-links estab-
 178 lished by progressive growth of secondary faults, such as breached relay ramps or trans-
 179 fer faults [e.g. *Gawthorpe and Hurst*, 1993; *Peacock*, 2002; *Trudgill and Cartwright*, 1994].

180 Scarp height on the Citsulo segment is too low to fit a bell-shaped height curve to
 181 the entire fault scarp (Fig. 2b). This low height, and the observation that the scarp is
 182 discontinuous near Citsulo, may indicate that the BMF comprises two separate faults.
 183 In this interpretation, there is no hard link between a 65 km long northern fault com-
 184 prising the four segments north of Citsulo, and a 30 km long southern fault represented
 185 by the Bilila segment.

186 Similar to other faults whose surface trace is discontinuous, the BMF may be con-
 187 tinuous at depth [e.g. *Nicol et al.*, 2005; *Worthington and Walsh*, 2016]. Note, however,
 188 that the low scarp height in the Citsulo segment may be related to local change in sur-
 189 face lithology. Whereas the majority of the fault displaces foliated, biotite-bearing gneisses,
 190 the scarp at Citsulo bends around poorly foliated, diopside-tremolite calc-silicate gran-
 191 ulite, which is both frictionally strong [*He et al.*, 2013] and lacks any pre-existing weak
 192 planes.

193 The BMF scarp parallels the strike of local foliation along 60% of its length (Fig.
 194 2a). Where the scarp locally bends to crosscut the foliation, e.g. Ngodzi and Mtakataka,
 195 such bends form high angle links between en echelon foliation-parallel scarps. These bends
 196 create a zig-zag pattern similar to other faults that locally reactivate weak planes [e.g.
 197 *McClay and Khalil*, 1998; *Bellahsen and Daniel*, 2005], except that the cross-foliation
 198 segments do not have a consistent strike (Fig. 2a). The only major segment that cross-
 199 cuts foliation along its full length is Mua, where foliation dips more gently than elsewhere
 200 along the scarp. This corroborates existing hypotheses that gently dipping structures
 201 are difficult to frictionally reactivate in rifts [e.g. *Collettini and Sibson*, 2001; *Phillips*
 202 *et al.*, 2016]. On the Ngodzi and Mtakataka segments, the scarp is steeper where it cross-
 203 cuts the foliation, and a more gentle scarp is also present on the foliation-parallel Kas-
 204 inje segment, compared to the Mua segment. Whilst to the first-order, the BMF scarp
 205 systematically appears steeper where it crosscuts foliation, a combination of factors in-
 206 cluding erosion rate, scarp age, footwall damage zone parameters, and original scarp shape
 207 influence the current scarp slope [*Arrowsmith et al.*, 1998; *Avouac*, 1993], and the inter-
 208 pretation of this tentative relation between scarp slope and foliation orientation is highly
 209 uncertain.

4.2 Relations between fault scarp geometry, local and regional stresses, and pre-existing structures

The average trend of the BMF scarp is comparable to the strike of the nearest instrumentally recorded earthquake, the 1989 Salima M_W 6.1 event (strike $154^\circ \pm 25^\circ$, dip $32^\circ \pm 5^\circ$, rake $-92^\circ \pm 25^\circ$), whose epicenter was ~ 40 km from the northern tip of the BMF scarp [Jackson and Blenkinsop, 1993]. Whereas a normal fault striking perpendicular to the current plate motion would strike $176^\circ \pm 5^\circ$ [Saria et al., 2014], the BMF average scarp trend fits well with the current local stress field estimated from focal mechanisms [$Sh_{min} = 062^\circ$ Delvaux and Barth, 2010]. This estimate, however, relies on only 13 earthquakes throughout the Malawi rift, and could reflect local strain as accommodated on reactivated faults rather than local stress [Twiss and Unruh, 1998]. However, reorientation of the local stress field along zones of weak fabric in rifts has been suggested to occur in close proximity to major border faults along the East African Rift System [Morley, 2010; Corti et al., 2013].

The BMF scarp is neither consistently parallel to foliation, nor in an orientation expected from current plate motion. We therefore propose that the fault segments are linked within the brittle zone to a deeper structure that controls the average surface trace (Fig. 4a). Variations in scarp height are greatest in the north (Fig. 2b), where very pronounced zig-zags in scarp trend are observed (Fig. 2a). We therefore infer that these peaks and troughs in scarp height, which have previously been interpreted as indicators of deeper segmented ruptures [e.g. Cartwright et al., 1996], may in fact result from local variations in fault geometry [e.g. Zielke et al., 2015; Mildon et al., 2016], here caused by heterogeneous reactivation of weak shallow fabrics above a broadly continuous structure. In fact, the local variability in BMF scarp geometry and morphology is similar to other scarps suggested to have formed due to reactivation of a deep structure [e.g., the Egiin Davaa scarp, Mongolia Walker et al., 2015]. Furthermore, the angular relationship between scarp trend and foliation strike at the surface on the BMF are also consistent with field observations by Pennacchioni and Mancktelow [2007], who describe reactivation of deeper structures in the ductile field, but that shallower brittle fractures largely crosscut cohesive, metamorphic structures and foliations, except where well oriented. We also note that the foliation-oblique scarp segments, big or small, do not have a consistent trend (Fig. 2a), as opposed to what one would expect if a consistent stress field, at the scale of the fault, controlled their orientation. Our findings are similar to those by Kolawole et al. [2018] for northern Malawi, who through field observations and aeromagnetic data suggest the 2009 Karonga earthquake sequence [Biggs et al., 2010] occurred on a deep structure that reactivated basement fabric. They found that the basement fabric was associated with the Precambrian Mughese Shear Zone, and the strike of the deep structure is oblique to the regional stress field. As inferred here, the deep structure likely caused a rotation of the local stress field, as suggested elsewhere along the East African Rift System [e.g. Morley, 2010; Corti et al., 2013].

The current scarp height along the BMF may also be evidence of reactivation of a pre-existing weakness at depth. As no fault plane slip direction indicators were found, we assume the faults are purely normal [Jackson and Blenkinsop, 1997; Chorowicz and Sorlien, 1992]. Under this assumption the scarp height may be used to represent the surface displacement [Morley, 2002], except where the scarp trend varies considerably from the average trend [Mackenzie and Elliott, 2017]. Relative to the fault length, the average vertical surface displacement (~ 14 m) is greater than would be expected by a single earthquake event [~ 6 m; Scholz, 2002], but the maximum surface displacement (~ 28 m) is significantly less than expected for the total displacement [$\sim 1,000$ m; Kim and Sanderson, 2005]. Although surface displacements may be several times less than those at depth [e.g., Villamor and Berryman, 2001], the BMF is still under-displaced compared to its length. This may suggest that the length of the BMF established rapidly in its slip history, before undergoing a current phase of displacement accumulation, i.e. following

263 the constant-length model of fault growth [e.g. *Walsh et al.*, 2002]. This fault growth model
 264 has been suggested to occur in reactivated faults systems where fault lengths are inher-
 265 ited from underlying structures [*Walsh et al.*, 2002]. As such, this morphological anal-
 266 ysis of the BMF is consistent with our structural interpretation that the fault is controlled
 267 by a pre-existing weak zone at depth oriented oblique to the regional stress direction.

268 4.3 A hypothesis test for a deep structure controlling the average sur- 269 face fault trace

270 To test our deep structure hypothesis, we construct a simple geometrical model to
 271 fit an irregular surface between the observed BMF scarp trend and an inferred planar
 272 deep structure (Fig. S1). Whereas we recognise that this deeper structure may itself be
 273 geometrically complex, segmented or controlled by subsurface fabrics, we assume a pla-
 274 nar form for simplicity of this hypothesis test. Slip is projected on the deep, planar struc-
 275 ture (assuming a bell-shaped along-strike slip profile, with constant slip down-dip) to the
 276 observed surface trace of the scarp (Fig. S1e). As no strike-slip offsets were found in the
 277 field or on the DEM, we assume that the slip direction on the deep structure is purely
 278 normal [*Jackson and Blenkinsop*, 1997; *Chorowicz and Sorlien*, 1992]. We then use the
 279 scarp trend orientation to calculate the vertical throw, and by using this as a proxy for
 280 scarp height [e.g. *Morewood and Roberts*, 2001], we compare against our measurements
 281 from the BMF scarp (Fig. 4b). We vary strike (ϕ), dip (δ), slip (u) and length (L) of the
 282 inferred structure, and the linking depth (Z_l) between this deeper structure and the fault
 283 segments observed at the surface.

284 Fixing the strike of the deep structure to be perpendicular to current plate motion
 285 (174°), and dip to be between 40° and 60° requires a linking depth greater than 25 km
 286 (RMSE ~ 8 m; Fig. S1c, 4b). This linking depth is approximately equal to, or greater
 287 than, the inferred fault locking depth in south Malawi [~ 30 km, *Jackson and Blenkin-*
 288 *sop*, 1993] and implies that if the fault formed in the current stress regime, it would ex-
 289 ist as a series of discontinuous segments. Inferring a deep structure that strikes sub-parallel
 290 to the average BMF scarp trend (150°), or is parallel to the strike of the 1989 Salima
 291 earthquake, however, produces a better match (RMSE 6-7 m) to the observed scarp height
 292 with a shallower linking depth (Fig. 4b). The best fitting continuous deep structure strikes
 293 141° , dips 22° , and requires a linking depth of 8 km and a slip of 49 m (RMSE ~ 6 m;
 294 Fig. 4b).

295 A single, continuous structure with $Z_l \leq 10$ km requires slip > 30 m, significantly
 296 more than anticipated in a single rupture [*Scholz*, 2002], but could represent cumulative
 297 slip from several events. Any single continuous structure we tested over-estimates the
 298 height of the Citsulo segment, whereas two deep faults (a 65 km long northern fault strik-
 299 ing 156° and a 30 km long southern fault striking 158°), separated by the Citsulo dis-
 300 continuity, better fit surface observations (RMSE ~ 4 m) and require a smaller amount
 301 of slip (Fig. 4b). The peaks and troughs in scarp height from all simulations broadly match
 302 the observations at the surface, suggesting that the surface displacement is influenced
 303 by the near-surface fault geometry [e.g. *Zielke et al.*, 2015; *Mildon et al.*, 2016].

304 More complex models might fit surface observations better; however, our calcula-
 305 tions confirm that the BMF surface expression is not compatible with a deep structure
 306 whose strike is perpendicular to the current E-W regional extension direction [*Saria et al.*,
 307 2014], but is compatible with upward propagation of a buried NW-SE striking weak zone
 308 [e.g. *Worthington and Walsh*, 2016].

309 5 Conclusions

310 Analysis of a high-resolution DEM and field observations suggest that the scarp
 311 of the ~ 110 km long Bilila-Mtakataka fault, Malawi, comprises six 10-40 km long seg-

312 ments. The scarp averages 14 m in height, but in places exceeds 25 m. This suggests that
 313 either multiple earthquake events have ruptured the segments, or a continuous rupture
 314 with an extraordinarily large amount of slip (> 30 m) has occurred. Although the scarp
 315 trace parallels the foliation for more than half of the fault length, large sections do not.
 316 We propose that the BMF scarp is a surface expression of a weak zone (or zones) at depth,
 317 that is not well oriented relative to regional extension, but whose strike is sub-parallel
 318 to both the average scarp trend and the strike of the largest magnitude earthquake in
 319 southern Malawi (the 1989 Salima event). A simple geometrical model does not reject
 320 this hypothesis, and indicates that BMF scarp height is likely influenced by the near-
 321 surface fault geometry, where locally well oriented metamorphic foliations are reactivated
 322 in preference over growth of new faults. Our findings are in agreement with others for
 323 north Malawi and elsewhere along the East African Rift System, and suggest deep, weak
 324 structures cause a reorientation of the local stress field. These conclusions highlight the
 325 importance of considering three-dimensional relationships over a range of length scales
 326 when interpreting fault scarps mapped at the surface.

327 **Figure 1.** (a) Geographical context of the Bilila-Mtakataka fault (BMF) scarp. S_{hmin} = mini-
 328 mum horizontal stress from *Delvaux and Barth* [2010], PM = current regional extension direction
 329 from *Saria et al.* [2014], EARS = East African Rift System, MRS = Malawi Rift System. For a
 330 map of the main structural features along the EARS please see Fig. S2 in the supporting infor-
 331 mation. (b) Geological map modified after *Walshaw* [1965] and *Dawson and Kirkpatrick* [1968].
 332 Light grey filled circles denote inferred intersegment zones (ISZ, Fig. 2). (c) Elevation profiles
 333 and hillshade digital elevation models (DEMs), numbers refer to locations in panel A. Definitions
 334 of upper and lower surfaces, and the method for deriving scarp height, H , follow *Avouac* [1993].
 335 Vertical exaggeration (VE) is displayed on the profiles.

336 **Figure 2.** Panels a-c are plots of distance along the Bilila-Mtakataka fault scarp against: (a)
 337 scarp trend and foliation strike from DEM and geological maps; (b) scarp height measured from
 338 DEM. Repeatable measurements are blue circles, and non-repeatable are red circles (error bars
 339 included). A 5 km moving average (solid blue line) and standard deviation (blue shaded area) are
 340 also given. Black and grey triangles mark major and minor rivers respectively; and (c) footwall
 341 lithology, see Fig. 1b for key (Mtk = Mtakataka). (d) Angular relationship between scarp trend
 342 (black), foliation strike (red), current regional extension direction [PM, black arrow; from *Saria*
 343 *et al.*, 2014], and planes perpendicular to current regional extension direction (\perp PM, black dotted
 344 line) and to local minimum horizontal stress [\perp S_{hmin} , grey dotted line; from *Delvaux and Barth*,
 345 2010]. (e) Map of BMF segments (coloured: Ng = Ngodzi; Mt = Mtakataka; Mu = Mua; Kj
 346 = Kasinje; Ct = Citsulo; and Bl = Bilila), including lower hemisphere, equal angle, stereoplots
 347 showing field measurements of scarp and basement rock foliation, indicating where the scarp
 348 follows (white) or cross-cuts (grey) local foliation.

349 **Figure 3.** Photographs of (a) Mua and (d) Kasinje knickpoints showing foliation (red) and
 350 fracture (blue) orientations from (b/e) above and on the (c/f) waterfall. For (c/f), where the wa-
 351 terfall is parallel to a foliation or fracture surface, the surface is coloured appropriately (i.e. red
 352 or blue). Foliation dips much more gently at Mua than Kasinje. The scarp trend and waterfall
 353 surface at the Mua knickpoint (setback 70 m from the scarp) cross-cut the high-grade metamor-
 354 phic foliation, whereas both are parallel to foliation at the Kasinje knickpoint that is setback 40
 355 m from the fault scarp.

356 **Figure 4.** (a) Schematic of the Bilila-Mtakataka fault, showing where it follows (red) or cross-
 357 cuts (purple) the high-grade metamorphic foliation, and an inferred link to a deep structure of
 358 strike ϕ and dip δ , at a linking depth Z_l . (b) Calculated scarp height, H , for the current BMF
 359 scarp if it is linked to a deep structure with maximum slip at the centre, for various deep struc-
 360 ture Z_l , ϕ , δ , maximum slip u and length L (Cont = continuous structure that strikes parallel to
 361 the average scarp trend; Sal = continuous structure with ϕ and δ from 1989 Salima earthquake;
 362 PM = continuous structure with a ϕ perpendicular to the current regional extension direction
 363 [taken from, *Saria et al.*, 2014]; BF = best-fitting continuous structure; and BF 2F = best-fitting
 364 scenario with two separate faults at depth). The observed BMF scarp height is also plotted for
 365 comparison (see table for RMSE). See the supplementary material for methodology (Fig. S1).

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