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## 25 **Abstract**

26 We present new insights on the geometry, initiation and growth of the Thyolo fault,  
27 an 85 km long active border fault in the southern Malawi Rift, from high-resolution  
28 topography, field and microstructural observations. The Thyolo fault is located  
29 towards the edge of the Proterozoic Unango Terrane, and is the border fault of the  
30 Lower Shire Graben, which has experienced four phases of extension since the  
31 Jurassic. Recent activity is demonstrated by an  $18.6 \pm 7.7$  m high fault scarp, with  
32 two substantial reductions in scarp height along strike. However, the segment  
33 boundaries suggested by these displacement measurements do not coincide with  
34 changes in fault strike. Elsewhere, a ~5 km long fault perpendicular scarp joins two  
35 overlapping sections, yet the scarp height in this linking section is similar to the  
36 bounding sections, and there is no evidence of significant pre-linkage strain  
37 accumulation. Microstructural analyses along the fault show a 15-45 m thick footwall  
38 damage zone with a 0.7 m thick core. We suggest that favourably-oriented, pre-  
39 existing shallow structures control changes in surface geometry and the narrow fault  
40 core, whereas exploitation of weak ductile zones at depth, possibly associated with  
41 the terrane boundary, control the displacement profile of the fault.

42

### 43 1. Introduction

44 Narrow amagmatic rifts (*sensu* Buck, 1991) are typically characterised by a  $\leq 100$  km  
45 wide graben or half graben where the greatest cumulative displacement is  
46 accommodated on large offset normal fault systems, known as rift border faults, that  
47 bound a region of distributed but relatively small displacement brittle deformation  
48 (Ebinger, 1989; Gawthorpe and Leeder, 2000; Muirhead et al., 2019). These basin-  
49 bounding faults are thought to be most active prior to any magmatic influence on  
50 rifting (Ebinger, 2005; Muirhead et al., 2019), have a distinctive impact on basin  
51 geomorphology (Leeder and Gawthorpe, 1987; Gawthorpe and Leeder, 2000) and  
52 can accumulate sufficient displacement to induce flexural bending within the hanging  
53 wall basin (Turcotte and Schubert, 2002). Border faults can penetrate the entire

54 depth of the crust, and in East Africa are probably the source of some of the deep  
55 earthquakes that occur within the 30-40 km thick seismogenic layer (Jackson and  
56 Blenkinsop, 1993; Craig et al., 2011; Lavayssière et al., 2019).

57

58 How faults grow from nucleation to crustal scale features is a long-standing topic of  
59 research (Cowie and Scholz, 1992b; Cowie, 1998; Walsh et al., 2002; Nicol et al.,  
60 2005; Worthington and Walsh, 2017; Rotevatn et al., 2019), and numerous studies  
61 have mapped fault trace geometry and measured displacement-length profiles to  
62 discuss the mechanism and timing of how long faults develop through segment  
63 initiation, growth, and linkage (Cowie and Scholz, 1992a, 1992b, 1992c; Scholz et  
64 al., 1993; Dawers et al., 1993; Dawers and Anders, 1995; Schlische et al., 1996;  
65 Walsh et al., 2003; Nicol et al., 2005, 2017; Giba et al., 2012; Rotevatn et al., 2018).

66 Structural heterogeneities at segment boundaries, such as fault bends and step-  
67 overs, are thought to influence the propagation and termination of earthquake  
68 ruptures (Segall and Pollard, 1980; Zhang et al., 1991; Wesnousky, 2006, 2008).

69 However, recent earthquakes (e.g. 2010  $M_w$ 7.2 El Mayor-Cucapah Earthquake,  
70 Mexico – Wei et al., 2011 and the 2016  $M_w$ 7.8 Kaikoura Earthquake, New Zealand –  
71 Hamling et al., 2017) have propagated across multiple segment boundaries, making  
72 it unclear how to best assess fault segmentation for seismic hazard purposes  
73 (DuRoss et al., 2016). Border faults are now generally thought to develop through  
74 the accumulation of displacement on fault segments that formed and linked during  
75 the early stages of rifting (Gawthorpe et al., 2003; Rotevatn et al., 2019; Muirhead et  
76 al., 2019); however, the effects of this linkage on the displacement profile and  
77 surface trace of a fault are commonly long-lasting (McLeod et al., 2008). Minima in  
78 fault displacement profiles are persistently observed at segment boundaries

79 (Machette et al., 1991; Gupta and Scholz, 2000; Mortimer et al., 2007, 2016) as are  
80 relay ramps, increased fault complexity, step-overs, and changes in fault orientation  
81 (Leeder and Gawthorpe, 1987; Crone and Haller, 1991a; Peacock and Sanderson,  
82 1991; Crider and Pollard, 1998; McLeod et al., 2008; Fossen and Rotevatn, 2016;  
83 Hodge et al., 2018a). Thus, observations of fault segmentation provide a permanent  
84 record of processes that occurred during the formation and linkage of fault  
85 segments, and consequently they offer insights into the fundamental processes of  
86 fault growth and the controls on the limits of earthquake rupture propagation.

87

88 Rifts rarely initiate and grow in isotropic crust, and therefore it is important to  
89 understand the effect of pre-existing heterogeneities and structures on the growth  
90 and segmentation of faults. These pre-existing structures are often cited as the  
91 predominant control on rift geometry, the distribution of strain within rifts, and the  
92 orientation of magmatic bodies, magmatic rift segments and faults within rifts  
93 (McConnell, 1967; Daly et al., 1989; Ebinger et al., 1997; Morley, 2010; Henstra et  
94 al., 2015; Robertson et al., 2016; Muirhead and Kattenhorn, 2018). At the scale of an  
95 individual fault, analogue models have shown that reactivation of pre-existing fabrics  
96 affects fault growth by influencing fault orientation, relay zone geometry and the  
97 distribution of basins (Bellahsen and Daniel, 2005; Henza et al., 2011). However,  
98 comparisons of these models with natural faults is challenging as it can be difficult to  
99 differentiate between contemporary and pre-rift heterogeneities that have similar  
100 geometries (Smith and Mosley, 1993; Holdsworth et al., 1997), especially using  
101 seismic reflection and aeromagnetic surveys, which can only resolve features at  
102 scales >10 m.

103

104 Investigating the interactions between pre-existing fabrics and strain localisation on  
105 rift border faults also requires understanding the structure and mechanics of these  
106 faults. In general, as faults grow, the rocks surrounding the fault accumulate damage  
107 (Cowie and Scholz, 1992b; Caine et al., 1996; Shipton and Cowie, 2003). However,  
108 the structure of a rift border fault has only been described in a limited number of  
109 cases (Ord et al., 1988; Wheeler and Karson, 1989; Kristensen et al., 2016;  
110 Hollinsworth et al., 2019), with most models of normal fault structural evolution based  
111 on studies of small displacement (<100 m) faults within high porosity sedimentary  
112 rock (Shipton and Cowie, 2003; Childs et al., 2009; Torabi and Berg, 2011; Savage  
113 and Brodsky, 2011). Consequently, it remains unclear whether these models are  
114 applicable to large offset rift border faults where the footwall is composed of foliated  
115 crystalline metamorphic rocks.

116

117 In this paper, we analyse the Thyolo fault, the border fault of the Lower Shire Graben  
118 in southern Malawi (Figure 1). The fault is an ideal location to study the effects of  
119 pre-existing structures on fault geometry and structure as the graben has a well-  
120 documented polyphase history of extension (Castaing, 1991; Chisenga et al., 2019).  
121 Furthermore, thin syn-rift sediments mean that fault exposures formed during the  
122 current rift phase are not hidden by post-rift sediments (e.g. Hodge et al., 2019;  
123 Williams et al., 2019). We begin by describing the tectonic history of the region,  
124 before analysing the current activity, geometry and structure of the fault. In doing so,  
125 we assess how reactivation of pre-existing fabrics and heterogeneities at different  
126 scales affects the evolution of a rift border fault.

127

128 2. Tectonic History

129 The Thyolo fault bounds the north-eastern edge of the Lower Shire Graben, which is  
130 located at the southern end of the largely amagmatic Western branch of the East  
131 African Rift (EAR; Figure 1). Extension within the Western branch of the EAR  
132 initiated ~25 Ma (Roberts et al., 2012) and within southern Malawi, the current  
133 horizontal geodetic extension rate is ~2 mm yr<sup>-1</sup> (relative to the stable Nubian plate;  
134 Stamps et al., 2018; Figure 1). It is not known whether this extension rate has been  
135 constant during the current phase of rifting (the last ~25 Ma).

136

137 The footwall of the Thyolo fault is composed of charnockitic gneiss and granitic  
138 granulites of the Mesoproterozoic Unango Terrane, part of the Mozambique Belt,  
139 with the fault located towards the southwestern edge of the terrane (Figure 2;  
140 Fullgraf et al. *in press*; Bloomfield, 1965; Johnson et al., 2005). The Unango Terrane  
141 likely formed in a continental volcanic arc setting at ~1 Ga, and experienced  
142 granulite facies metamorphism associated with ductile deformation shortly after  
143 emplacement ( $957 \pm 27$  Ma; Bingen et al., 2009). The metamorphic foliation and  
144 migmatitic banding in the Thyolo fault's footwall dips moderately SW. The foliation  
145 formed at granulite facies metamorphic conditions coincident with partial melting  
146 during a series of collisional events at a convergent continental margin in the Pan-  
147 African Orogeny (~710-555 Ma) associated with the amalgamation of Gondwana  
148 (Kröner et al., 2001; Johnson et al., 2005; Manda et al., 2019). In the region of the  
149 Thyolo fault, the edge of the Unango Terrane is in contact with the basement of the  
150 South Irumide Belt, which underwent peak metamorphism between 1.06 and 1.05  
151 Ga (Johnson et al., 2005; Westerhof et al., 2008; Karmakar and Schenk, 2016). The  
152 terrane boundaries have been roughly mapped based on exposures within Malawi  
153 (Manda et al., 2019), but because younger cover sequences (~330-180 Ma Karoo-

154 age sedimentary rocks) have obscured the basement, the unit boundaries are largely  
155 extrapolated from neighbouring Mozambique, where mapping was supported by  
156 geochemical and airborne magnetic data (Bingen et al., 2009; Macey et al., 2010).

157

## 158 2.1 Previous phases of rifting

159 The Lower Shire Graben contains Phanerozoic sedimentary and volcanic deposits  
160 related to three regional phases of extension that occurred prior to the current rifting  
161 (i.e. prior to ~25 Ma): two distinct events during the Karoo-age breakup of Gondwana  
162 (~330-180 Ma), and a later phase at the end of the Jurassic and into the early  
163 Cretaceous (~140-110 Ma; Castaing, 1991; Figure 2).

164

165 NW-SE Karoo-age transtension in the Lower Shire Graben created space to deposit  
166 a sequence of Late Ecca (Middle Permian) to Late Beaufort (Early Triassic) coal  
167 shales, coarse grained grits, mudstones and sandstones (orange units in Figure 2c).  
168 These sedimentary rocks are bound by E-W striking normal faults and NW-SE  
169 striking dextral strike-slip faults including the Mwanza and possibly the Thyolo fault  
170 (Figure 2c; Habgood, 1963; Habgood et al., 1973; Castaing, 1991).

171

172 NW-SE extension continued into the late Karoo period, when it was associated with  
173 basaltic volcanism and contemporaneous emplacement of NE-SW striking dolerite  
174 dykes. These dykes and volcanic deposits are collectively known as the Stormberg  
175 Volcanics, which are widely observed in the footwalls of the Mwanza, Thyolo and  
176 Mtumba faults (Figure 2d; Habgood, 1963; Habgood et al., 1973; Woolley et al.,  
177 1979; Castaing, 1991).

178

179 After the Karoo period, during the Late Jurassic – Cretaceous, the extension  
180 direction rotated from NW-SE to NE-SW and reactivated NW-SE structures  
181 established in the earlier phase of NW-SE transtension as dip-slip normal faults  
182 (Figure 2e; Castaing, 1991). In the Lower Shire Graben, remnant deposits from the  
183 NE-SW extension are limited to sandstones in the hanging wall of the Panga and  
184 Chitumba faults (Figure 2e) and siliceous fault rock along the Namalambo Fault  
185 (Habgood, 1963; Habgood et al., 1973). These sedimentary deposits form part of the  
186 Lupata series, a mix of coarse grained sandstones, and rhyolitic and alkaline lavas  
187 found extensively in Mozambique (Dixey and Campbell Smith, 1929; Habgood,  
188 1963), and were emplaced contemporaneously with the Chilwa Alkaline Province,  
189 which involves intrusive rocks that crosscut the Stormberg dykes (Macdonald et al.,  
190 1983; Woolley, 1987; Castaing, 1991; Eby et al., 1995). Cretaceous activity on the  
191 Thyolo and/or Mwanza faults cannot be ruled out as current syn-rift sediments will  
192 likely have buried any Cretaceous sedimentary deposits.

193

## 194 2.2 Current rifting

195 Previous studies have interpreted the Thyolo fault as an active, reactivated dextral  
196 strike-slip fault linking the Urema Graben (the southern active continuation of the  
197 EARS in Mozambique) and the Zomba Graben (Castaing, 1991; Chorowicz and  
198 Sorlien, 1992; Chorowicz, 2005). In other studies, the Thyolo fault is considered  
199 inactive (Lañ-Dávila et al., 2015; Prater et al., 2016). Hodge et al. (2019) combined  
200 remote sensing observations with field observations to show that the fault is active,  
201 by documenting a pseudo-continuous fault scarp and triangular facets at the  
202 southern end of the fault. However, the fault was divided into two separate faults, the  
203 Thyolo and Muona faults, based on the separation distance between their scarps

204 (Hodge et al., 2019). A  $M_w$ 5.6 earthquake in March 2018 had a normal faulting focal  
205 mechanism with nodal planes aligned with the surface traces of faults in the Lower  
206 Shire Graben (Figure 1; Ekström et al., 2012). Williams et al. (2019) suggest that the  
207 Thyolo fault is currently active as a dip-slip normal fault oriented obliquely to the  
208 ENE-WSW regional extension direction. Below, we describe in detail the dimensions  
209 and geometry of the fault scarp, and the fault damage zone along the Thyolo fault,  
210 and analyse the factors that control fault segmentation, orientation and structure.

211

### 212 3. Methodology

#### 213 3.1 Fault segmentation analysis

214 We used a high resolution 12 m TanDEM-X digital elevation model (DEM) to identify  
215 different indicators of fault segmentation based on two distinct sets of criteria: map-  
216 view geometry and scarp height. We mapped the fault trace in high resolution and  
217 noted prominent changes in fault strike, map-view fault steps, fault branches,  
218 increased fault complexity or gaps, which are considered geometrical indicators of  
219 fault segmentation (Zhang et al., 1991; Wesnousky, 2008; DuRoss et al., 2016).

220

221 Fault segmentation can also be defined from the along-fault displacement profile  
222 (e.g. Dawers and Anders, 1995; Willemse et al., 1996; Willemse, 1997; Walsh et al.,  
223 2003). In a plot of fault displacement vs. fault-parallel distance, the segment  
224 boundaries are usually located at local displacement minima (Crone and Haller,  
225 1991a; Dawers and Anders, 1995; Walsh et al., 2003). We used scarp height as a  
226 proxy for displacement (e.g. Morewood and Roberts, 2000; Hodge et al., 2018b,  
227 2019; Wedmore et al., 2020) and identified segments based on local minima in the  
228 along-strike scarp height profile. We used adapted versions of the SPARTA scarp

229 measuring tools (Hodge et al., 2019) to measure the height of the fault scarp along  
230 the Thyolo fault on the 12 m DEM. We differ from Hodge et al. (2019) by extracting  
231 500 m long fault-perpendicular topographic profiles from the DEM every 12 m along  
232 the fault, which were averaged by stacking at 100 m intervals before measuring the  
233 vertical difference between regression lines on the footwall and hanging wall  
234 surfaces. We estimated the uncertainty of each measurement by applying a Monte  
235 Carlo approach to sample 10,000 random subsets of points from the hanging wall  
236 and footwall of the fault as well as allowing the location of the fault to vary along the  
237 section of the topographic profiles identified as the fault scarp. The resulting  
238 measurements of vertical offset were then filtered using a 5 km wide moving median  
239 filter along the strike of the fault.

240

241 We also examined the Thyolo fault for any evidence of features associated with fault  
242 linkage. Where two un-linked fault segments interact, fractures and faults form such  
243 that the faults maintain laterally constant extensional strain (Walsh and Watterson,  
244 1991). These features create relay zones or transfer structures, which evolve as the  
245 faults overlap and link. Typically relay structures have 10-15° dipping ramps and  
246 breach structures that link the segments (Fossen and Rotevatn, 2016). Before a  
247 linking fault has breached a relay ramp, propagating and overlapping fault tips  
248 induces rotation (about a vertical axis) within the transfer structure (Fossen and  
249 Rotevatn, 2016). To identify linking structures, we analysed variations in the strike of  
250 the fault by dividing the fault trace into 50 m long sections and measuring the strike  
251 of each section from the trend of the surface trace, assuming negligible topography.  
252 The orientation of pre-existing basement structures were analysed by digitising the

253 3D foliation measurements and strike of dolerite (Stormberg) dykes in Habgood et al.  
254 (1973).

255

256 The fault scarp and geometry of some of the structures that we observed in the  
257 remote sensing data and geological maps were ground-truthed during field  
258 campaigns in 2017 and 2018, during which additional observations were made  
259 regarding the structure and slip sense of the fault.

260

### 261 3.2 Fault zone meso- and microstructural analysis

262 We made lithological and structural observations of the footwall damage zone of the  
263 Thyolo fault along four transects, Kalulu, Kanjedza, Mbewe, and Muona (Figure 3),  
264 which extended from the fault scarp to distances up to 280 m into the footwall. In  
265 addition, we collected samples at Kalulu ( $n = 5$ ) and Kanjedza ( $n = 11$ ) for  
266 microstructural and compositional analyses. Individual samples were accurately  
267 located using digital elevation models and orthophotos constructed from drone-  
268 based photogrammetry, as well as handheld GPS measurements. Sample thin  
269 sections were photographed in plane-polarised and cross-polarised light, and  
270 fracture density was calculated from manually traced fractures in three 10-15 mm<sup>2</sup>  
271 areas in each sample using FracPaQ 2.2 (Healy et al., 2017). We only traced  
272 fractures in quartz or feldspar grains, to allow comparison between lithologically  
273 diverse samples, and used an area-weighted average as the fracture density value  
274 for each thin section (see supplementary text for full details of sample collection,  
275 preparation and analysis).

276

## 277 4. Results

#### 278 4.1 The Thyolo Fault

279 The Thyolo fault has a recently active fault scarp at the base of a ~1 km high footwall  
280 escarpment (Figure 3 & 4). Note that we consider the previously described Thyolo  
281 and Muona faults as a singular 'Thyolo fault', rather than two separate structures (in  
282 contrast to Hodge et al., 2019) because the Chisumbi link section connects the  
283 Thyolo and Muona sections of the fault without a break in the scarp (Figures 3-5 and  
284 Section 4.4). Triangular facets are visible within the high-resolution topography along  
285 the southeastern end of the Thyolo section and the northwestern end of the Muona  
286 section (Figure 3), and were also observed in the field (Figure 4). We observed no  
287 systematic deflection of river channels or any other geomorphological features that  
288 might indicate strike-slip faulting (Figure S1), and we therefore consider the Thyolo  
289 fault to be currently accommodating pure normal dip-slip displacement (see also  
290 Williams et al., 2019).

291

#### 292 4.2 Map View Geometry

293 The Thyolo fault is ~85 km long and has a mean strike of  $139 \pm 15^\circ$  (1 standard  
294 deviation) dipping to the southwest (Figure 3 & 4). A fault scarp is visible in the high-  
295 resolution topography along the length of the fault, with gaps observed where  $\leq 100$   
296 m wide rivers cross the fault and have eroded the scarp (Figure 3b). However, the  
297 effect of rivers on the observations in Figure 5 is negligible as we did not measure  
298 scarps in these locations, and the final scarp height is averaged over 5 km along  
299 strike to smooth short-wavelength features such as these rivers. We find seven  
300 sections along the fault trace that trend approximately perpendicular to the average  
301 fault strike (Figure 5c). These NE-SW oriented sections have a mean strike of  $044 \pm$   
302  $28^\circ$  (black lines in Figure 5) with five sections dipping to the northwest and two

303 sections dipping to the southeast. The dip angle of these NE-SW oriented sections is  
304 unknown but is likely  $>30^\circ$  based on the slope of the facet in the escarpment above  
305 (Figure 6; Tucker et al., 2011). The most prominent of these NE-SW sections forms  
306 a 4.8 km orthogonal link between the Thyolo and Muona sections (Figure 6). The  
307  $\sim 69$  km long Thyolo and the  $\sim 28$  km long Muona sections overlap by  $\sim 10$  km and are  
308 connected by this 4.8 km long section, which we refer to as the Chisumbi section.  
309 The six other scarp sections that trend perpendicular to the average fault strike are  
310 each  $<500$  m long.

311

312 The mean strike of the pre-existing metamorphic foliation, within the footwall  
313 basement of the Thyolo fault, is  $140 \pm 37^\circ$  with a dip of  $56 \pm 12^\circ$  SW (Figure 5 & 6).  
314 This is subparallel to the mean strike of the fault scarp ( $139 \pm 15^\circ$ ; Figure 5). A fault  
315 dip could only be constrained in the field at Kalulu, nevertheless, this measurement  
316 ( $60^\circ$ ) and the range of active normal fault dips elsewhere in Malawi ( $45^\circ$ - $60^\circ$ ; Hodge  
317 et al., 2018b; Kolawole et al., 2018; Williams et al., 2019) and globally (Colletini and  
318 Sibson, 2001) suggest that the Thyolo fault dips subparallel to the foliation.  
319 Conversely, the mean strike of the dolerite dykes in the fault's footwall (calculated by  
320 digitising the orientation of the contact between the dyke and basement rock) is  $037$   
321  $\pm 9^\circ$ , which is within error of the strike-perpendicular sections of the fault ( $044 \pm 28^\circ$ ;  
322 including the Chisumbi section). Our field measurements at four localities along the  
323 Thyolo Fault indicate that the dykes are subvertical (Figure 3a).

324

#### 325 4.3 Scarp Height

326 The median height of the fault scarp along the Thyolo fault is  $18.6 \pm 7.7$  m (Figure 5).  
327 The along-strike profile of the scarp height measurements shows two scarp height

328 minima (besides the fault tips; Figure 5b). The distance from the north-western fault  
329 tip to the first minimum is 28 km with a median scarp height of  $24.9 \pm 9.0$  m in this  
330 portion of fault (Figure 5b). The middle portion of the fault is 15 km long and has a  
331 median scarp height of  $20.8 \pm 6.3$  m. The south-eastern portion is 48 km long with  
332 median scarp height of  $17.8 \pm 6.5$  m (Figure 5b). None of the scarp height minima  
333 identified from the scarp height profile coincide with changes in fault strike, i.e. the  
334 short segments that trend perpendicular to the average fault strike (Figure 5). The  
335 scarp height minimum that occurs at  $\sim 53$  km on Figure 5 is adjacent to a region  
336 where the foliation strike varies within a range of  $\sim 70^\circ$  around the mean. The region  
337 contains both typical and somewhat anomalous orientations, and although it may be  
338 an area of structural complexity, it does not stand out as markedly different from  
339 elsewhere along the fault.

340

#### 341 4.4 The Chisumbi Section

342 The 4.8 km Chisumbi section links the Muona and Thyolo sections (Figure 4b) and  
343 has a strike of  $046 \pm 31^\circ$ , which is approximately orthogonal ( $93 \pm 34^\circ$ ) to the  
344 average strike of the main fault ( $139 \pm 15^\circ$ ) but subparallel to the average strike of  
345 the dolerite dykes ( $037 \pm 9^\circ$ ; Figure 6). Along this linking section, we observed a  $19.0$   
346  $\pm 4.2$  m high scarp (median value; see example profile D in Figure 3b; Figure 5). This  
347 height (yellow triangle in Figure 5b) is within the error bounds of the scarps found  
348 along the adjacent Muona and Thyolo sections. Thus, the fault scarp along Chisumbi  
349 section trends approximately perpendicular to the bounding sections, but has a  
350 similar scarp height.

351

352 Within the footwall of the Chisumbi section, where the Muona and Thyolo sections  
353 overlap, the dolerite dykes have a strike of  $031 \pm 9^\circ$  whereas the strike of the dolerite  
354 dykes outside the overlap zone is  $038 \pm 9^\circ$  (Figure 6b). Thus, as these values are  
355 within the error bounds of each other, the average trace of dykes within the  
356 overlapping zone have either no rotation or a slight anticlockwise rotation around a  
357 vertical axis (Figure 6b). The dip of the topography in the footwall of the Chisumbi  
358 section (excluding the facet slope above the fault scarp) is  $2^\circ$  (Figure 6c),

359

#### 360 4.5 Damage zone and fault core structure of the Thyolo fault

##### 361 4.5.1 Lithology

362 The contact between hanging-wall sediments, and footwall gneisses and granulites  
363 of the Unango Terrane, is exposed at Kalulu (Figure 7), where these two units are  
364 separated by an approximately  $60^\circ$  dipping, 0.7 m thick, incohesive white to minty  
365 green fault gouge. The gouge contains a brown clay-rich matrix (70-90% by area)  
366 with subangular to subrounded quartzofeldspathic clasts (10-30% by area) up to 3  
367 mm in size (Figures 7b and S2). A 5-15 m thick zone of incohesive  
368 quartzofeldspathic granulite and hornblende gneiss borders the fault gouge. At the  
369 other three localities where field exposures of the fault were studied, a 15-45 m wide  
370 unit of incohesive biotite  $\pm$  hornblende  $\pm$  pyroxene gneiss is present adjacent to the  
371 scarp, beyond which, the gneiss appears more intact (Figures 8 and S3). The  
372 gneissic foliation is defined by alternating quartzofeldspathic and biotite  $\pm$  hornblende  
373  $\pm$  garnet bands, in which elongate biotite grains are aligned to and also define a  
374 foliation subparallel to the compositional banding. Subvertical, NE-SW striking  
375 Stormberg dolerite dykes crosscut the gneisses at all distances from the fault.

376

377 4.5.2 Fault zone structure

378 Quartzofeldspathic clasts within the fault gouge at Kalulu are intensely fractured and  
379 sheared (Figure 7), and therefore we interpret this 0.7 m zone as the fault core  
380 (sensu Caine et al., 1996). In the incohesive gneisses and granulites in the footwall  
381 beyond the fault core, the metamorphic foliation and pegmatite veins are generally  
382 preserved (Figure 9 and S4), although locally offset by  $< 0.6$  m along minor faults  
383 (i.e. discrete secondary faults within the footwall of the main fault; Figure 8d). At  
384 Kanjedza, a 2 m wide ductile reverse shear zone has been exploited by a NW-SE  
385 striking dyke whose emplacement predates movement on the Thyolo fault, as it has  
386 been offset by a minor normal fault (Figure 8c). At Mbewe, a 50 cm thick, scarp-  
387 parallel, steeply dipping foliated fault gouge is present 10 m into the footwall, and  
388 juxtaposes charnockite and locally folded hornblende gneisses (Figure S3).

389

390 In the incohesive gneisses  $< 50$  m from the Thyolo fault, quartz and feldspar grains  
391 exhibit fracture densities of  $2.3-4.8 \text{ mm}^{-1}$ , with most fractures oblique to the foliation  
392 (Figure 9 and Figure S5). These fractures are generally intragranular and closed, but  
393 there are rare cases of biotite and calcite mineralisation, which are most prevalent  
394 close to minor faults and/or dykes (Figure 9b). Microscale fracture density within the  
395 intact gneisses 50-280 m from the Thyolo fault is  $0.9-2.2 \text{ mm}^{-1}$ , and fractures are  
396 almost exclusively parallel to the foliation (Figure 9e). We interpret the 15-45 m wide  
397 unit of incohesive gneiss with a relatively high density of foliation-oblique  
398 microfractures, but little evidence of shear displacement, as the footwall damage  
399 zone (sensu Caine et al., 1996). At distances  $> 45$  m from the fault, the gneiss is  
400 intact, and there is no major changes in composition. Therefore, we are confident  
401 that the incohesive nature of the damage zone is related to brittle deformation and

402 fracturing around the fault, and any physical weathering or chemical alteration is  
403 enhanced by and linked to fault-related fracture damage.

404

405 We do not observe a systematic decay in fracture density with distance from the fault  
406 within the 15-45 m wide damage zone of the Thyolo fault (Figure 9). This may reflect  
407 damage around minor faults and dykes within the damage zone (e.g. Figure 9b), the  
408 lack of consistently oriented samples with respect to the fault, a sample bias that  
409 misses the most damaged rocks because they are impossible to sample intact,  
410 and/or variations in grain size and composition. The microfracture density increase  
411 inside the damage zone relative to the background level is relatively minor (Figure  
412 9g; compare with Wilson et al., 2003; Mitchell and Faulkner, 2009). It is difficult to  
413 assess if this small increase in fracture density represents a relatively low fracture  
414 density in the damage zone, or selective sampling of more cohesive portions of the  
415 damage zone for analysis.

416

## 417 5. Discussion

418 The  $18.6 \pm 7.7$  m fault scarp and triangular facets indicate that the Thyolo fault has  
419 been reactivated during the current stage of East African Rifting (since 25 Ma),  
420 although the steepness of the scarp indicates that it probably formed in the Late-  
421 Quaternary or it would have degraded further (Hodge et al., 2020). Whereas the  
422 Thyolo fault is dominantly subparallel to the metamorphic foliation, there are notable  
423 sections where the strike turns by  $\sim 90^\circ$  and the fault scarp trends subparallel to the  
424 strike of Stormberg-age subvertical dolerite dykes (Figure 6).

425

### 426 5.1 Fault segmentation

427 Scarp height minima and changes in surface fault trend are generally considered  
428 indicators of fault segment boundaries (Crone and Haller, 1991b; Machette et al.,  
429 1991; Peacock and Sanderson, 1991; Crider and Pollard, 1998; Mortimer et al.,  
430 2007, 2016; Fossen and Rotevatn, 2016). However, along the Thyolo fault, the  
431 locations of scarp height minima do not coincide with changes in the trend of the  
432 fault scarp (Figure 5).

433

434 The sections that trend perpendicular to the overall strike of the Thyolo fault range in  
435 length from 170 m to 4.8 km. Because of our method of measuring strike as a 50 m  
436 average, we may have missed < 50 m long strike-perpendicular sections that  
437 coincide with the scarp height minima. However, we do not see short fault-  
438 perpendicular sections near the scarp height minima on the scarp maps made from  
439 the 12 m DEM. Only one of the fault-perpendicular sections (the Chisumbi section)  
440 would normally be considered long enough to be a segment boundary based on  
441 geometrical criteria (i.e.  $\geq \sim 3\text{-}5$  km; Wesnousky, 2008). This geometry has been  
442 used to argue that the Thyolo and Muona sections are different faults (Hodge et al.,  
443 2019). However, a previously unrecognised fault scarp along the Chisumbi section  
444 links the Thyolo and Muona sections, and the height of this scarp is in the same  
445 range as scarps along the bounding Thyolo and Muona sections (Figure 3b, profile  
446 D; Figure 5b). The presence of this continuous scarp implies that during the recent  
447 earthquakes that formed the scarp, slip likely propagated along and through the 4.8  
448 km long,  $\sim 90^\circ$  kink in the fault. Given the  $\sim 600$  m high escarpment and triangular  
449 facets along the Chisumbi section it is also likely that slip has persistently  
450 propagated along this section over longer geological time, through what would  
451 typically be considered geometrical segment boundaries (Figure 10c). Consequently,

452 on faults that have reactivated pre-existing fabrics, purely geometrical criteria for  
453 identifying fault segmentation may not adequately identify segment boundaries.

454

455 The Chisumbi section lacks evidence for distributed strain in the area between the  
456 tips of the Thyolo and Muona sections it links (Figure 10). There is no or minor  
457 anticlockwise rotation of dykes in the footwall of the Chisumbi section, and the  
458 topographic slope dips at a much shallower angle ( $\sim 2^\circ$ ; Figure 10) compared to a  
459 global study of the dip of breached relay ramps (10-15°; Fossen and Rotevatn,  
460 2016). Although the comparatively gentle ramp dip may be because most examples  
461 in the global catalogue are from sedimentary rocks, it remains clear that little strain  
462 accumulated within the Chisumbi section prior to the bounding Thyolo and Muona  
463 sections becoming linked. The morphology of the Chisumbi linkage section is most  
464 similar to a mid-ramp relay zone breach (Figure 10), which appears to be favoured in  
465 locations with brittle basement rock and/or where pre-existing structures are  
466 reactivated (Fossen and Rotevatn, 2016). When the distance between bounding  
467 sections is less than 20% of their total fault length, Hodge et al. (2018a) suggest that  
468 breaching occurs as slip is promoted by positive Coulomb stress changes in the  
469 linking region. As the  $\sim 5$  km Chisumbi section is  $<20\%$  of the  $\sim 80$  km Thyolo fault,  
470 we propose that the Thyolo and Muona sections are linked by weak structures that  
471 were activated by Coulomb stress changes in the shallow upper crust. This linkage  
472 occurred prior to the accumulation of significant strain within the relay zone, and the  
473 link section no longer operates as a permanent barrier to earthquake rupture and  
474 propagation (Figure 10d).

475

476 5.2 Thyolo fault zone structure

477 The Thyolo fault has a ~1 km high footwall escarpment, which suggests that the total  
478 displacement across the fault is at least 1.2 km (assuming a 60° fault dip) and the  
479 damage zone documented here reflects fault-related deformation within a kilometre  
480 of the surface. The 15-45 m thick footwall damage zone is within the range of other  
481 faults with km-scale displacement in global comparisons, whereas the 0.7 m fault  
482 core is relatively narrow (Torabi and Berg, 2011; Savage and Brodsky, 2011; Torabi  
483 et al., 2019). However, there is considerable scatter in these global comparisons  
484 owing to variations in fault kinematics, lithology and depth of faulting. A more  
485 instructive comparison may be to the Dombjerg fault, Greenland, which is another  
486 well exposed rift border fault of similar scale to the Thyolo fault (3 km throw, ~100 km  
487 long), with a footwall hosted in crystalline metamorphic basement rocks that contain  
488 a fault-parallel gneissic foliation. The Dombjerg fault footwall damage zone is 600 m  
489 wide, ~10 times wider than the Thyolo fault, and the core comprises several <0.5 m  
490 thick strands of gouge and breccia in a ~200 m wide zone, (Kristensen et al., 2016),  
491 whereas the single Thyolo fault core is 0.7 m thick. The thicker and more distributed  
492 nature of the Dombjerg fault core compared to the Thyolo fault core may reflect that  
493 the Dombjerg fault was studied near a step between two fault segments (Kristensen  
494 et al., 2016). On the other hand, our observations from the Thyolo fault were taken  
495 from sites where there is no obvious geometrical complexity. The smaller fault zone  
496 thickness and localised, single fault core in the Thyolo fault support theories where  
497 the distribution of fault complexities during initiation and growth control fault zone  
498 width (Kim and Sanderson, 2005; Childs et al., 2009). Localised slip and a narrow  
499 damage zones are observed for other faults that follow pre-existing discontinuities  
500 (Heermance et al., 2003; Zangerl et al., 2006), and so the fault-parallel foliation may  
501 have also contributed to the Thyolo fault's relatively narrow structure. Therefore,

502 where a fault such as the Thyolo fault initiates, grows and lengthens rapidly in  
503 mechanically anisotropic crust, a narrow damage zone and core initially forms, prior  
504 to any increase in damage that may occur with the accumulation of larger  
505 displacements (e.g. Kolyokhin and Torabi, 2012).

506

### 507 5.3 Mechanism of fault reactivation

508 Within amagmatic portions of the East African Rift System, immature faults (Biggs et  
509 al., 2010), strong, cold intact crust (Fagereng, 2013) and low b-values recorded  
510 during seismic sequences (Gaherty et al., 2019; Lavayssière et al., 2019) are all  
511 suggestive of high differential stress in the region. Furthermore, wall-rock and gouge  
512 samples from the Thyolo fault at Kalulu do not contain significant amounts of  
513 frictionally weak, authigenic phyllosilicate minerals (Williams et al., 2019),  
514 deformation experiments on representative lithologies from the Malawi Rift indicate  
515 that they are frictionally strong (coefficient of friction,  $\mu_s > 0.55$ ; Hellebrekers et al.,  
516 2019), and the thick (30-40 km) seismogenic crust suggests that the frictional-  
517 viscous transition does not occur at shallow depths (Craig et al., 2011; Fagereng,  
518 2013). The Thyolo fault is, however, generally oriented parallel or subparallel to  
519 basement foliation and possibly also NW-SE striking dykes (Figure 5-6, 8c), implying  
520 that reactivation of these pre-existing structures is preferred over initiation and  
521 growth of new fault surfaces. There is no evidence that the faults host authigenic  
522 minerals and clays as described in other, long-term, frictionally weak faults described  
523 in the shallow crust elsewhere (e.g. Holdsworth, 2004; Jefferies et al., 2006).

524

525 We suggest that the foliation and dykes play an important role in controlling the  
526 geometry of the Thyolo fault in the shallow crust by providing relatively well-oriented

527 planes for reactivation, on which the sum of cohesion and frictional resistance in the  
528 current stress field is less on the pre-existing plane than the intact rock. Although  
529 well-oriented interconnected biotite foliation may be slightly weaker than the wall-  
530 rock (Behnsen and Faulkner, 2012), such planes are not obviously controlling the  
531 fault (Figure 7,8 & 9), and a combination of greater phyllosilicate content and low  
532 cohesion, compared to the wall-rock, is likely why the foliations and dyke margins  
533 are reactivated near-surface. This is consistent with fault reactivation analysis from  
534 southern Malawi, which suggests that moderately dipping NW-SE striking incohesive  
535 surfaces will reactivate even if they are slightly oblique to the ENE-WSW to E-W  
536 trending minimum principal compressive stress (Williams et al., 2019). The Thyolo  
537 fault zone contains an incohesive damage zone and fault core (Figures 7 and 8), and  
538 we do not see fault zone fluid flow indicators in our microstructural and field  
539 observations (e.g. vein networks or fault zone alteration; Wästeby et al., 2014;  
540 Williams et al., 2017) that could result in fault cohesion recovery or the growth of  
541 frictionally weak minerals (Tenthorey and Cox, 2006; Holdsworth et al., 2011)

542

543 We also suggest that interlinked mechanisms of reactivation of pre-existing surfaces  
544 and dynamic stress reorientation along the Thyolo fault may explain why some fault  
545 sections are orientated nearly perpendicular to the strike of the main fault. The  
546 overlapping geometry between the Thyolo and Muona sections may have been  
547 established early in the growth history of the Thyolo fault by the exploitation of pre-  
548 existing NW-SE striking surfaces, on which reactivation is preferred over creating  
549 new failure surfaces in the current stress field (Williams et al., 2019). Coulomb stress  
550 changes within relay zones are known to favour the creation of zigzag fault patterns  
551 (Crider and Pollard, 1998), and coseismic Coulomb stress changes around bounding

552 faults with large overlaps favour high angle link structures rather than oblique  
553 breached relay ramps or the creation of a fault bend (Hodge et al., 2018a). These  
554 links may have originated as transform faults, as they are better oriented for  
555 transform motion, and later reactivated as normal faults, although no evidence for  
556 transform motion is preserved. Slip on orthogonal structures may also have been  
557 favoured by the presence of Stormberg dolerite dykes striking perpendicular to the  
558 Thyolo fault (Figure 6a). Although linking segments coinciding with a pre-existing  
559 dyke have not been directly observed, the margins of dykes in swarms cutting  
560 basement terrains are commonly reactivated during later deformation events  
561 (Holdsworth et al., 2020), and dolerite dykes in South Africa are known to have  
562 increased brittle damage along the dyke-basement contact zone that reduces  
563 cohesion (Senger et al., 2015). In summary, we propose that co-seismic stress  
564 changes on overlapping faults favoured shallow activation of high-angle low-  
565 cohesion zones at the contact between the pre-existing dykes and the basement, as  
566 opposed to an oblique relay zone; in this context, linkage of the Thyolo faults proto-  
567 sections could have occurred relatively quickly.

568

569 Although the Thyolo fault surface trace follows near-surface weaknesses, this  
570 mechanism is less applicable at depths where cohesion is maintained, the relative  
571 strength differences between foliations, dykes, and intact rock are smaller, and/or  
572 confining stresses too high for frictional failure. Because variably striking normal  
573 faults at shallow depth in anisotropic crust are thought to link to and initiate from  
574 more continuous structures at depth (e.g. Graymer et al., 2007; Walker et al., 2017;  
575 Hodge et al., 2018b), these near-surface low cohesion or weaker (relative to the  
576 wall-rock) fabrics alone are not sufficient to account for the geometry of the Thyolo

577 fault at depth. In this case, it is notable that the Thyolo fault is located at or towards  
578 the edge of the Unango Terrane. Although the exact nature and location of this  
579 boundary is uncertain, it represents a high metamorphic grade boundary at the edge  
580 of the Pan-African orogenic belts. Another regional example of these boundaries  
581 includes the Lurio Belt, which borders the Nampula Complex in NE Mozambique and  
582 is observed in outcrops of mylonitic sheared leucogneiss (Bingen et al., 2009; Macey  
583 et al., 2010). If the Unango Terrane boundary is similar to this other high  
584 metamorphic grade boundary, it could represent an existing shear zone that is  
585 viscously weak because of small grain size (Watterson, 1975; Fliervoet et al., 1997;  
586 Stenvall et al., 2019), foliation of interconnected low viscosity minerals (Handy, 1990;  
587 Montési, 2013), crystal-preferred orientations conducive to plastic flow (Poirier,  
588 1980), or provide a competency contrast across the boundary that leads to increased  
589 stress and therefore a localisation of strain (Goodwin and Tikoff, 2002). At least  
590 some of these features apply to the quartz-feldspar-biotite gneissic foliation in the  
591 Thyolo fault footwall, and would make the foliation conducive to viscous reactivation.  
592 Consequently, we consider it likely that the Thyolo fault follows a more continuous  
593 deep-seated structure (Figure 11), possibly associated with ductile reactivation of the  
594 boundary of the Unango Terrane at mid-crustal level.

595

596 Although many faults, including the Bilila-Mtakataka fault in the Makanjira Graben,  
597 Malawi (Figure 1; Hodge et al., 2018b), show both displacement minima and  
598 geometrical changes (or structural complexity) at the same locations (Peacock and  
599 Sanderson, 1991; Dawers and Anders, 1995; Walsh et al., 2003), this is clearly not  
600 the case for the Thyolo fault (Figure 5). Dyke margins and foliation planes that shape  
601 the surface trace of the Thyolo fault have not influenced the along-strike scarp height

602 profile (Figure 5). Instead, we suggest that if the Thyolo fault is also following a more  
603 continuous structure at depth, possibly a ductile weakness associated with the edge  
604 of the Unango Terrane, then it is the heterogeneities in this weakness that dictate  
605 where along-strike variations in fault displacement are located. We refer to this as  
606 depth-dependent reactivation.

607

608 Where depth-dependent reactivation occurs, a combination of structural controls  
609 affect the fault geometry and displacement in different ways (Phillips and McCaffrey,  
610 2019). The Thyolo fault is an example of where the fault structure at the surface is  
611 guided by shallow pre-existing fabrics and structures, which have influenced the fault  
612 orientation, the fault core and damage zone and the relay zone evolution. In contrast,  
613 deeper reactivated structures, which we suggest may be associated with ductile  
614 reactivation of shear zones at high-grade metamorphic boundaries, can explain the  
615 slightly oblique orientation of the Thyolo fault to the regional extension direction yet  
616 apparent dip-slip kinematics (see modelling by Philippon et al., 2015; Hodge et al.,  
617 2018b; Williams et al., 2019, and observations from Phillips et al., 2016; Phillips and  
618 McCaffrey, 2019), the location of scarp height minima, and its continual reactivation  
619 under a diverse range of previous extensional directions within the Lower Shire  
620 Graben (Castaing, 1991). We acknowledge the model where the primary control on  
621 rift growth is likely to be lithospheric strength (Ebinger et al., 1991); however, while  
622 the total fault length and displacement profile may indeed reflect a thick elastic crust,  
623 the detailed surface fault geometry appears affected by a combination of shallower  
624 brittle and deeper viscous structural elements.

625

626 5.4 Comparison with other continental rifts and grabens

627 Many of the aspects of reactivation that we observe along the Thyolo fault resemble  
628 features observed in other parts of the active East African Rift System. Localised  
629 deformation, and fast growth and linkage of the Thyolo border fault is comparable to  
630 the Okavango rift, which is also inferred to be localised along a long-lived pre-  
631 existing crustal-scale weak zone (Kinabo et al., 2007, 2008). If local fabrics only  
632 control the shallow orientation of the fault, this also explains why individual faults in  
633 Malawi can both crosscut and follow the metamorphic foliation (Hodge et al., 2018b).  
634 Furthermore, our model explains the difference between the Lower Shire Graben,  
635 where the largest topographic relief indicates that the majority of displacement  
636 occurs on the border fault (the Thyolo fault; Figure 1), and the Zomba Graben to the  
637 north, where displacement is distributed more evenly between border and intrabasin  
638 faults (Wedmore et al., 2020). Lateral heterogeneity within the lower crust beneath  
639 the Zomba Graben has been inferred to cause this more heterogeneous strain  
640 distribution, possibly by multiple localised shear zones at depth guiding distributed  
641 deformation in the upper crust and at the surface (Wedmore et al., 2020). This is a  
642 preferred explanation for strain distribution in the Zomba Graben, as it is located  
643 *within* the Unango Terrane. In contrast, the Lower Shire Graben is located towards  
644 the edge of the terrane and hence the deformation may localise towards the terrane  
645 boundary.

646

647 The northern North Sea basin is another example of a multiphase rift where faults  
648 are hosted in crystalline basement rocks. Here, lithospheric thinning and heating, as  
649 well as stress feedbacks between growing faults, control the rift-scale localisation of  
650 strain, with pre-existing shallow brittle faults thought to have little control on  
651 reactivation (Cowie et al., 2005; Claringbould et al., 2017). Along the Thyolo fault, we

652 have shown that shallow features affect the geometry but not the displacement  
653 profile of the fault. This is consistent with the results from the North Sea basin,  
654 suggesting that reactivation of shallow pre-existing structures and fabrics may have  
655 only a surficial role in controlling the geometry but not the accumulation of  
656 displacement of faults in rifts within crystalline, dry, continental crust. This differs  
657 from studies where a major role in rift evolution has been suggested for upper crustal  
658 faults (e.g. Bellahsen & Daniel, 2005; Duffy et al., 2015; Heilman et al., 2019;  
659 Katumwehe et al., 2015; Laõ-Dávila et al., 2015; Whipp et al., 2014). This confirms  
660 the need to consider the scale- and depth-dependence of pre-existing structures  
661 when assessing fault reactivation, where the pre-existing weaknesses may control  
662 macro- but not meso-scale structural development (Kirkpatrick et al., 2013; Samsu et  
663 al., 2020).

664

## 665 5.5 Implications for seismic hazard assessment

666 Geometrical criteria to define fault segments are commonly used to assess rupture  
667 scenarios for seismic hazard assessments (Crone and Haller, 1991a; Lettis et al.,  
668 2002; Wesnousky, 2008). We find that earthquake ruptures have persistently  
669 propagated through significant changes in fault geometry and suggest that shallow  
670 brittle structures only have a superficial, geometric effect on fault segmentation.  
671 Instead, the displacement profile may provide a better indication of fault segment  
672 boundaries controlled by a deeper, more continuous structure (Figure 11). This result  
673 differs from findings on the Wasatch fault, USA, where DuRoss et al. (2016) suggest  
674 that displacement profiles have limited value for identifying segment boundaries that  
675 restrict earthquake ruptures. Thus, our findings may only apply in regions where pre-  
676 existing fabrics play an important role in guiding the surface geometry of a fault. This

677 presents a challenge when segmentation criteria based on shallow structures is used  
678 for assessing earthquake magnitudes for seismic hazard analyses (e.g. Field et al.,  
679 2009; Petersen et al., 2015; Valentini et al., 2019): where depth-dependent  
680 segmentation is not correctly identified, multi-segment and multi-fault ruptures such  
681 as those observed in the 2016 earthquakes in central Italy ( $M_w$ 6.2, 6.1 & 6.6) and  
682 Kaikoura, New Zealand ( $M_w$ 7.8) or the 2010  $M_w$ 7.2 El Mayor-Cucapah, Mexico  
683 earthquake (Wei et al., 2011; Hamling et al., 2017; Walters et al., 2018) may become  
684 more likely than is apparent from surficial indicators of fault segmentation.

685

## 686 6. Conclusion

687 The Thyolo fault is the major border fault of the Lower Shire Graben, which has  
688 experienced at least three previous phases of Phanerozoic rifting. Long sections of  
689 the fault have a NW-SE strike, but these are separated by short sections that strike  
690 NE-SW. The largest NE-SW section, the Chisumbi section, is 4.8 km long, which is  
691 normally considered long enough to define a separate fault segment that  
692 accumulates displacement differently from adjacent segments. However, the location  
693 of both the Chisumbi section and other shorter sections with a prominent change in  
694 strike do not align with two segment boundaries identified by along-strike variations  
695 in the height of the active fault scarp. We find that the fault and the pre-existing  
696 foliation are broadly parallel, whereas the strike of the short sections orientated NE-  
697 SW matches the strike of dykes emplaced during a previous period of Karoo-age  
698 rifting. Using field and microstructural observations of the Thyolo fault's footwall, we  
699 estimate that the footwall fault zone is between 15-45 m wide, considerably narrower  
700 than another example of a rift bounding fault in crystalline metamorphic basement  
701 (the Dombjerg fault, Greenland; Kristensen et al., 2016). All these observations

702 suggest that the shallow, near-surface portions of the fault are reactivating well-  
703 oriented foliation planes and near-perpendicularly oriented dyke contacts that act as  
704 weak surfaces in the shallow crust compared to the crystalline basement. However,  
705 these shallow pre-existing structures have not affected the distribution of the most  
706 recent, near-surface displacement recorded by the scarp along the fault. Instead, we  
707 suggest that the fundamental control on the growth and displacement accumulation  
708 of this rift border fault is controlled by a broadly continuous structure at depth, which  
709 is likely to be controlled by viscous reactivation of mid-crustal ductile heterogeneities,  
710 possibly associated with the edge of the Unango Terrane.

711

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725 **References**

- 726 Behnsen, J., and Faulkner, D.R., 2012, The effect of mineralogy and effective normal  
727 stress on frictional strength of sheet silicates: *Journal of Structural Geology*, v.  
728 42, p. 49–61, doi:10.1016/j.jsg.2012.06.015.
- 729 Bellahsen, N., and Daniel, J.M., 2005, Fault reactivation control on normal fault  
730 growth: An experimental study: *Journal of Structural Geology*, v. 27, p. 769–780,  
731 doi:10.1016/j.jsg.2004.12.003.
- 732 Biggs, J., Nissen, E., Craig, T., Jackson, J., and Robinson, D.P., 2010, Breaking up  
733 the hanging wall of a rift-border fault: The 2009 Karonga earthquakes, Malawi:  
734 *Geophysical Research Letters*, v. 37, p. 1–5, doi:10.1029/2010GL043179.
- 735 Bingen, B., Jacobs, J., Viola, G., Henderson, I.H.C., Skår, Ø., Boyd, R., Thomas,  
736 R.J., Solli, A., Key, R.M., and Daudi, E.X.F., 2009, Geochronology of the  
737 Precambrian crust in the Mozambique belt in NE Mozambique, and implications  
738 for Gondwana assembly: *Precambrian Research*, v. 170, p. 231–255,  
739 doi:10.1016/j.precamres.2009.01.005.
- 740 Bloomfield, K., 1965, The geology of the Zomba Area: *Bulletin of the Geological*  
741 *Survey, Malawi*, v. 16.
- 742 Buck, W.R., 1991, Modes of continental lithospheric extension: *Journal of*  
743 *Geophysical Research: Solid Earth*, v. 96, p. 20161–20178,  
744 doi:10.1029/91JB01485.
- 745 Caine, J.S., Evans, J.P., and Forster, C.B., 1996, Fault zone architecture and  
746 permeability structure: *Geology*, v. 24, p. 1025–1028, doi:10.1130/0091-  
747 7613(1996)024<1025:FZAAPS>2.3.CO;2.
- 748 Castaing, C., 1991, Post-Pan-African tectonic evolution of South Malawi in relation to  
749 the Karroo and recent East African rift systems: *Tectonophysics*, v. 191, p. 55–

750 73, doi:10.1016/0040-1951(91)90232-H.

751 Childs, C., Manzocchi, T., Walsh, J.J., Bonson, C.G., Nicol, A., and Schöpfer, M.P.J.,  
752 2009, A geometric model of fault zone and fault rock thickness variations:  
753 Journal of Structural Geology, v. 31, p. 117–127, doi:10.1016/j.jsg.2008.08.009.

754 Chisenga, C., Dulanya, Z., and Jianguo, Y., 2019, The structural re-interpretation of  
755 the Lower Shire Basin in the Southern Malawi rift using gravity data: Journal of  
756 African Earth Sciences, v. 149, p. 280–290,  
757 doi:10.1016/j.jafrearsci.2018.08.013.

758 Chorowicz, J., 2005, The East African rift system: Journal of African Earth Sciences,  
759 v. 43, p. 379–410, doi:10.1016/j.jafrearsci.2005.07.019.

760 Chorowicz, J., and Sorlien, C., 1992, Oblique extensional tectonics in the Malawi  
761 Rift, Africa: Geological Society of America Bulletin, v. 104, p. 1015–1023,  
762 doi:10.1130/0016-7606(1992)104<1015:OETITM>2.3.CO;2.

763 Claringbould, J.S., Bell, R.E., Jackson, C.A.L., Gawthorpe, R.L., and Odinsen, T.,  
764 2017, Pre-existing normal faults have limited control on the rift geometry of the  
765 northern North Sea: Earth and Planetary Science Letters, v. 475, p. 190–206,  
766 doi:10.1016/j.epsl.2017.07.014.

767 Collettini, C., and Sibson, R.H., 2001, Normal faults, normal friction? Geology, v. 29,  
768 p. 927, doi:10.1130/0091-7613(2001)029<0927:NFNF>2.0.CO;2.

769 Cowie, P.A., 1998, A healing-reloading feedback control on the growth rate of  
770 seismogenic faults: Journal of Structural Geology, v. 20, p. 1075–1087,  
771 doi:10.1016/S0191-8141(98)00034-0.

772 Cowie, P.A., and Scholz, C.H., 1992a, Displacement-length scaling relationship for  
773 faults: data synthesis and discussion: Journal of Structural Geology, v. 14, p.  
774 1149–1156, doi:10.1016/0191-8141(92)90066-6.

775 Cowie, P.A., and Scholz, C.H., 1992b, Growth of faults by accumulation of seismic  
776 slip: *Journal of Geophysical Research*, v. 97, p. 11085, doi:10.1029/92JB00586.

777 Cowie, P.A., and Scholz, C.H., 1992c, Physical explanation for the displacement-  
778 length relationship of faults using a post-yield fracture mechanics model: *Journal*  
779 *of Structural Geology*, v. 14, p. 1133–1148, doi:10.1016/0191-8141(92)90065-5.

780 Cowie, P.A., Underhill, J.R., Behn, M.D., Lin, J., and Gill, C.E., 2005, Spatio-  
781 temporal evolution of strain accumulation derived from multi-scale observations  
782 of Late Jurassic rifting in the northern North Sea: A critical test of models for  
783 lithospheric extension: *Earth and Planetary Science Letters*, v. 234, p. 401–419,  
784 doi:10.1016/j.epsl.2005.01.039.

785 Craig, T.J., Jackson, J.A., Priestley, K., and Mckenzie, D., 2011, Earthquake  
786 distribution patterns in Africa: Their relationship to variations in lithospheric and  
787 geological structure, and their rheological implications: *Geophysical Journal*  
788 *International*, v. 185, p. 403–434, doi:10.1111/j.1365-246X.2011.04950.x.

789 Crider, J.G., and Pollard, D.D., 1998, Fault linkage: Three-dimensional mechanical  
790 interaction between echelon normal faults: *Journal of Geophysical Research:*  
791 *Solid Earth*, v. 103, p. 24373–24391, doi:10.1029/98jb01353.

792 Crone, A.J., and Haller, K.M., 1991a, Segmentation and the coseismic behavior of  
793 Basin and Range normal faults: examples from east-central Idaho and  
794 southwestern Montana, U.S.A.: *Journal of Structural Geology*, v. 13, p. 151–  
795 164, doi:10.1016/0191-8141(91)90063-O.

796 Crone, A.J., and Haller, K.M., 1991b, Segmentation and the coseismic behavior of  
797 Basin and Range normal faults: examples from east-central Idaho and  
798 southwestern Montana, U.S.A.: *Journal of Structural Geology*, v. 13, p. 151–  
799 164, doi:10.1016/0191-8141(91)90063-O.

800 Daly, M.C., Chorowicz, J., and Fairhead, J.D., 1989, Rift basin evolution in Africa:  
801 The influence of reactivated steep basement shear zones: Geological Society  
802 Special Publication, v. 44, p. 309–334, doi:10.1144/GSL.SP.1989.044.01.17.

803 Dawers, N.H., and Anders, M.H., 1995, Displacement-length scaling and fault  
804 linkage: *Journal of Structural Geology*, v. 17, p. 607–614, doi:10.1016/0191-  
805 8141(94)00091-D.

806 Dawers, N.H., Anders, M.H., and Scholz, C.H., 1993, Growth of normal faults:  
807 displacement-length scaling: *Geology*, v. 21, p. 1107–1110, doi:10.1130/0091-  
808 7613(1993)021<1107:GONFDL>2.3.CO;2.

809 Dixey, F., and Campbell Smith, W., 1929, The rocks of the Lupata Gorge and the  
810 north side of the lower Zambezi: *Geological Magazine*, v. 66, p. 241–259.

811 Duffy, O.B., Bell, R.E., Jackson, C.A.L., Gawthorpe, R.L., and Whipp, P.S., 2015,  
812 Fault growth and interactions in a multiphase rift fault network: Horda Platform,  
813 Norwegian North Sea: *Journal of Structural Geology*, v. 80, p. 99–119,  
814 doi:10.1016/j.jsg.2015.08.015.

815 DuRoss, C.B., Personius, S.F., Crone, A.J., Olig, S.S., Hylland, M.D., Lund, W.R.,  
816 and Schwartz, D.P., 2016, Fault segmentation: New concepts from the Wasatch  
817 Fault Zone, Utah, USA: *Journal of Geophysical Research: Solid Earth*, v. 121, p.  
818 1131–1157, doi:10.1002/2015JB012519.

819 Ebinger, C., 2005, Continental break-up: The East African perspective: *Astronomy  
820 and Geophysics*, v. 46, p. 2.16-2.21, doi:10.1111/j.1468-4004.2005.46216.x.

821 Ebinger, C.J., 1989, Geometric and kinematic development of border faults and  
822 accommodation zones, Kivu-Rusizi Rift, Africa: *Tectonics*, v. 8, p. 117–133,  
823 doi:10.1029/TC008i001p00117.

824 Ebinger, C., Djomani, Y.P., Mbede, E., Foster, A., and Dawson, J.B., 1997, Rifting

825        Archaean lithosphere: the Eyasi-Manyara-Natron rifts, East Africa: *Journal of the*  
826        *Geological Society*, v. 154, p. 947–960, doi:10.1144/gsjgs.154.6.0947.

827   Ebinger, C.J., Karner, G.D., and Weissel, J.K., 1991, Mechanical strength of  
828        extended continental lithosphere: Constraints from the Western Rift System,  
829        East Africa: *Tectonics*, v. 10, p. 1239–1256, doi:10.1029/91TC00579.

830   Eby, G.N., Roden-Tice, M., Krueger, H.L., Ewing, W., Faxon, E.H., and Woolley,  
831        A.R., 1995, Geochronology and cooling history of the northern part of the Chilwa  
832        Alkaline Province, Malawi: *Journal of African Earth Sciences*, v. 20, p. 275–288,  
833        doi:10.1016/0899-5362(95)00054-W.

834   Ekström, G., Nettles, M., and Dziewoński, A.M., 2012, The global CMT project 2004-  
835        2010: Centroid-moment tensors for 13,017 earthquakes: *Physics of the Earth*  
836        *and Planetary Interiors*, v. 200–201, p. 1–9, doi:10.1016/j.pepi.2012.04.002.

837   Fagereng, Å., 2013, Fault segmentation, deep rift earthquakes and crustal rheology:  
838        Insights from the 2009 Karonga sequence and seismicity in the Rukwa-Malawi  
839        rift zone: *Tectonophysics*, v. 601, p. 216–225, doi:10.1016/j.tecto.2013.05.012.

840   Field, E.H. et al., 2009, Uniform California Earthquake Rupture Forecast, Version 2  
841        (UCERF 2): *Bulletin of the Seismological Society of America*, v. 99, p. 2053–  
842        2107, doi:10.1785/0120080049.

843   Fliervoet, T.F., White, S.H., and Drury, M.R., 1997, Evidence for dominant grain-  
844        boundary sliding deformation in greenschist- and amphibolite-grade  
845        polymineralic ultramylonites from the Redbank Deformed Zone, Central  
846        Australia: *Journal of Structural Geology*, v. 19, p. 1495–1520,  
847        doi:10.1016/S0191-8141(97)00076-X.

848   Fossen, H., and Rotevatn, A., 2016, Fault linkage and relay structures in extensional  
849        settings-A review: *Earth-Science Reviews*, v. 154, p. 14–28,

850 doi:10.1016/j.earscirev.2015.11.014.

851 Fullgraf, T., Dombola, K., Hyvonen, E., Thomas, B., and Zammit, C. The Provisional  
852 GEMMAP 1:1 Million Scale structural and geological maps of Malawi:  
853 Geological Survey of Malawi,.

854 Gaherty, J.B. et al., 2019, Faulting processes during early-stage rifting: Seismic and  
855 geodetic analysis of the 2009-2010 Northern Malawi earthquake sequence:  
856 Geophysical Journal International, v. 217, p. 1767–1782,  
857 doi:10.1093/gji/ggz119.

858 Gawthorpe, R.L., Jackson, C.A.-L., Young, M.J., Sharp, I.R., Moustafa, A.R., and  
859 Leppard, C.W., 2003, Normal fault growth, displacement localisation and the  
860 evolution of normal fault populations: the Hammam Faraun fault block, Suez rift,  
861 Egypt: Journal of Structural Geology, v. 25, p. 883–895, doi:10.1016/S0191-  
862 8141(02)00088-3.

863 Gawthorpe, R.L., and Leeder, M.R., 2000, Tectono-sedimentary evolution of active  
864 extensional basins: Basin Research, v. 12, p. 195–218, doi:10.1111/j.1365-  
865 2117.2000.00121.x.

866 Giba, M., Walsh, J.J., and Nicol, A., 2012, Segmentation and growth of an obliquely  
867 reactivated normal fault: Journal of Structural Geology, v. 39, p. 253–267,  
868 doi:10.1016/j.jsg.2012.01.004.

869 Goodwin, L.B., and Tikoff, B., 2002, Competency contrast, kinematics, and the  
870 development of foliations and lineations in the crust: Journal of Structural  
871 Geology, v. 24, p. 1065–1085, doi:10.1016/S0191-8141(01)00092-X.

872 Graymer, R.W., Langenheim, V.E., Simpson, R.W., Jachens, R.C., and Ponce, D.A.,  
873 2007, Relatively simple through-going fault planes at large-earthquake depth  
874 may be concealed by the surface complexity of strike-slip faults: Geological

875 Society, London, Special Publications, v. 290, p. 189–201,  
876 doi:10.1144/SP290.5.

877 Gupta, A., and Scholz, C.H., 2000, A model of normal fault interaction based on  
878 observations and theory: *Journal of Structural Geology*, v. 22, p. 865–879,  
879 doi:10.1016/S0191-8141(00)00011-0.

880 Habgood, F., 1963, The geology of the country west of the Shire River between  
881 Chikwawa and Chiromo: *Bulletin of the Geological Survey, Malawi*, v. 14.

882 Habgood, F., Holt, D.N., and Walshaw, R.D., 1973, The geology of the Thyolo Area:  
883 *Bulletin of the Geological Survey, Malawi*, v. 22.

884 Hamling, I.J. et al., 2017, Complex multifault rupture during the 2016 Mw 7.8  
885 Kaikōura earthquake, New Zealand: *Science*, v. 356,  
886 doi:10.1126/science.aam7194.

887 Handy, M.R., 1990, The solid-state flow of polymineralic rocks: *Journal of*  
888 *Geophysical Research*, v. 95, p. 8647, doi:10.1029/JB095iB06p08647.

889 Healy, D., Rizzo, R.E., Cornwell, D.G., Farrell, N.J.C., Watkins, H., Timms, N.E.,  
890 Gomez-Rivas, E., and Smith, M., 2017, FracPaQ: A MATLAB™ toolbox for the  
891 quantification of fracture patterns: *Journal of Structural Geology*, v. 95, p. 1–16,  
892 doi:10.1016/j.jsg.2016.12.003.

893 Heermance, R., Shipton, Z.K., and Evans, J.P., 2003, Fault structure control on fault  
894 slip and ground motion during the 1999 rupture of the Chelungpu fault, Taiwan:  
895 *Bulletin of the Seismological Society of America*, v. 93, p. 1034–1050,  
896 doi:10.1785/0120010230.

897 Heilman, E., Kolawole, F., Atekwana, E.A., and Mayle, M., 2019, Controls of  
898 Basement Fabric on the Linkage of Rift Segments: *Tectonics*, v. 38, p. 1337–  
899 1366, doi:10.1029/2018TC005362.

900 Hellebrekers, N., Niemeijer, A.R., Fagereng, Å., Manda, B., and Mvula, R.L.S., 2019,  
901 Lower crustal earthquakes in the East African Rift System: Insights from  
902 frictional properties of rock samples from the Malawi rift: *Tectonophysics*, v. 767,  
903 p. 228167, doi:10.1016/j.tecto.2019.228167.

904 Henstra, G.A., Rotevatn, A., Gawthorpe, R.L., and Ravnås, R., 2015, Evolution of a  
905 major segmented normal fault during multiphase rifting: The origin of plan-view  
906 zigzag geometry: *Journal of Structural Geology*, v. 74, p. 45–63,  
907 doi:10.1016/j.jsg.2015.02.005.

908 Henza, A.A., Withjack, M.O., and Schlische, R.W., 2011, How do the properties of a  
909 pre-existing normal-fault population influence fault development during a  
910 subsequent phase of extension? *Journal of Structural Geology*, v. 33, p. 1312–  
911 1324, doi:10.1016/j.jsg.2011.06.010.

912 Hodge, M., Biggs, J., Fagereng, Å., Elliott, A., Mdala, H., and Mphepo, F., 2019, A  
913 semi-automated algorithm to quantify scarp morphology (SPARTA): Application  
914 to normal faults in southern Malawi: *Solid Earth*, v. 10, p. 27–57, doi:10.5194/se-  
915 10-27-2019.

916 Hodge, M., Biggs, J., Fagereng, Å., Mdala, H., Wedmore, L.N.J., and Williams, J.N.,  
917 2020, Evidence From High-Resolution Topography for Multiple Earthquakes on  
918 High Slip-to-Length Fault Scarps: The Bilila-Mtakataka Fault, Malawi: *Tectonics*,  
919 v. 39, doi:10.1029/2019TC005933.

920 Hodge, M., Fagereng, and Biggs, J., 2018a, The Role of Coseismic Coulomb Stress  
921 Changes in Shaping the Hard Link Between Normal Fault Segments: *Journal of*  
922 *Geophysical Research: Solid Earth*, v. 123, p. 797–814,  
923 doi:10.1002/2017JB014927.

924 Hodge, M., Fagereng, Biggs, J., and Mdala, H., 2018b, Controls on Early-Rift

925           Geometry: New Perspectives From the Bilila-Mtakataka Fault, Malawi:  
926           Geophysical Research Letters, v. 45, p. 3896–3905,  
927           doi:10.1029/2018GL077343.

928   Holdsworth, R.E., 2004, Weak Faults--Rotten Cores: Science, v. 303, p. 181–182,  
929           doi:10.1126/science.1092491.

930   Holdsworth, R.E., Butler, C.A., and Roberts, A.M., 1997, The recognition of  
931           reactivation during continental deformation: Journal of the Geological Society, v.  
932           154, p. 73–78, doi:10.1144/gsjgs.154.1.0073.

933   Holdsworth, R.E., van Diggelen, E.W.E., Spiers, C.J., de Bresser, J.H.P., Walker,  
934           R.J., and Bowen, L., 2011, Fault rocks from the SAFOD core samples:  
935           Implications for weakening at shallow depths along the San Andreas Fault,  
936           California: Journal of Structural Geology, v. 33, p. 132–144,  
937           doi:10.1016/j.jsg.2010.11.010.

938   Holdsworth, R.E., Selby, D., Dempsey, E., Scott, L., Hardman, K., Fallick, A.E., and  
939           Bullock, R., 2020, The nature and age of Mesoproterozoic strike-slip faulting  
940           based on Re–Os geochronology of syntectonic copper mineralization, Assynt  
941           Terrane, NW Scotland: Journal of the Geological Society, p. jgs2020- 011,  
942           doi:10.1144/jgs2020-011.

943   Hollinsworth, A.D., Koehn, D., Dempster, T.J., and Aanyu, K., 2019, Structural  
944           controls on the interaction between basin fluids and a rift flank fault: Constraints  
945           from the Bwamba Fault, East African Rift: Journal of Structural Geology, v. 118,  
946           p. 236–249, doi:10.1016/j.jsg.2018.10.012.

947   Jackson, J., and Blenkinsop, T., 1993, THE Malaŵi Earthquake of March 10, 1989:  
948           DEep faulting within the East African Rift System: Tectonics, v. 12, p. 1131–  
949           1139, doi:10.1029/93TC01064.

950 Jefferies, S.P., Holdsworth, R.E., Shimamoto, T., Takagi, H., Lloyd, G.E., and Spiers,  
951 C.J., 2006, Origin and mechanical significance of foliated cataclastic rocks in the  
952 cores of crustal-scale faults: Examples from the Median Tectonic Line, Japan:  
953 Journal of Geophysical Research: Solid Earth, v. 111, p. n/a-n/a,  
954 doi:10.1029/2005JB004205.

955 Johnson, S.P., Rivers, T., and De Waele, B., 2005, A review of the Mesoproterozoic  
956 to early Palaeozoic magmatic and tectonothermal history of south–central  
957 Africa: implications for Rodinia and Gondwana: Journal of the Geological  
958 Society, v. 162, p. 433–450, doi:10.1144/0016-764904-028.

959 Karmakar, S., and Schenk, V., 2016, Mesoproterozoic UHT metamorphism in the  
960 Southern Irumide Belt, Chipata, Zambia: Petrology and in situ monazite dating:  
961 Precambrian Research, v. 275, p. 332–356,  
962 doi:10.1016/j.precamres.2016.01.018.

963 Katumwehe, A.B., Abdelsalam, M.G., and Atekwana, E.A., 2015, The role of pre-  
964 existing Precambrian structures in rift evolution: The Albertine and Rhino  
965 grabens, Uganda: Tectonophysics, v. 646, p. 117–129,  
966 doi:10.1016/j.tecto.2015.01.022.

967 Kim, Y.S., and Sanderson, D.J., 2005, The relationship between displacement and  
968 length of faults: A review: Earth-Science Reviews, v. 68, p. 317–334,  
969 doi:10.1016/j.earscirev.2004.06.003.

970 Kinabo, B.D., Atekwana, E.A., Hogan, J.P., Modisi, M.P., Wheaton, D.D., and  
971 Kampunzu, A.B., 2007, Early structural development of the Okavango rift zone,  
972 NW Botswana: Journal of African Earth Sciences, v. 48, p. 125–136,  
973 doi:10.1016/j.jafrearsci.2007.02.005.

974 Kinabo, B.D., Hogan, J.P., Atekwana, E.A., Abdelsalam, M.G., and Modisi, M.P.,

975 2008, Fault growth and propagation during incipient continental rifting: Insight  
976 from a combined aeromagnetic and Shuttle Radar Topography Mission digital  
977 elevation model investigation of the Okavango Rift Zone, northwest Botswana:  
978 *Tectonics*, v. 27, p. 1–16, doi:10.1029/2007TC002154.

979 Kirkpatrick, J.D., Bezerra, F.H.R., Shipton, Z.K., Do Nascimento, A.F., Pytharouli,  
980 S.I., Lunn, R.J., and Soden, A.M., 2013, Scale-dependent influence of pre-  
981 existing basement shear zones on rift faulting: A case study from NE Brazil:  
982 *Journal of the Geological Society*, v. 170, p. 237–247, doi:10.1144/jgs2012-043.

983 Kolawole, F., Atekwana, E.A., Laó-Dávila, D.A., Abdelsalam, M.G., Chindandali,  
984 P.R., Salima, J., and Kalindekafe, L., 2018, High resolution electrical resistivity  
985 and aeromagnetic imaging reveal the causative fault of the 2009 Mw 6.0  
986 Karonga, Malawi Earthquake: *Geophysical Journal International*, v. 213, p. 1–  
987 47, doi:10.1093/gji/ggy066.

988 Kristensen, T.B., Rotevatn, A., Peacock, D.C.P., Henstra, G.A., Midtkandal, I., and  
989 Grundvåg, S.A., 2016, Structure and flow properties of syn-rift border faults: The  
990 interplay between fault damage and fault-related chemical alteration (Dombjerg  
991 Fault, Wollaston Forland, NE Greenland): *Journal of Structural Geology*, v. 92,  
992 p. 99–115, doi:10.1016/j.jsg.2016.09.012.

993 Kröner, A., Willner, A.P., Hegner, E., Jaeckel, P., and Nemchin, A., 2001, Single  
994 zircon ages, PT evolution and Nd isotopic systematics of high-grade gneisses in  
995 southern Malawi and their bearing on the evolution of the Mozambique belt in  
996 southeastern Africa: *Precambrian Research*, v. 109, p. 257–291,  
997 doi:10.1016/S0301-9268(01)00150-4.

998 Laó-Dávila, D.A., Al-Salmi, H.S., Abdelsalam, M.G., and Atekwana, E.A., 2015,  
999 Hierarchical segmentation of the Malawi Rift: The influence of inherited

1000 lithospheric heterogeneity and kinematics in the evolution of continental rifts:  
1001 Tectonics, v. 34, p. 2399–2417, doi:10.1002/2015TC003953.

1002 Lavayssière, A., Drooff, C., Ebinger, C., Gallacher, R., Illsley-Kemp, F., Oliva, S.J.,  
1003 and Keir, D., 2019, Depth Extent and Kinematics of Faulting in the Southern  
1004 Tanganyika Rift, Africa: Tectonics, v. 38, p. 842–862,  
1005 doi:10.1029/2018TC005379.

1006 Leeder, M.R., and Gawthorpe, R.L., 1987, Sedimentary models for extensional tilt-  
1007 block/half-graben basins: Geological Society, London, Special Publications, v.  
1008 28, p. 139–152, doi:10.1144/GSL.SP.1987.028.01.11.

1009 Lettis, W., Bachhuber, J., Witter, R., Brankman, C., Randolph, C.E., Barka, A., Page,  
1010 W.D., and Kaya, A., 2002, Influence of Releasing Step-Overs on Surface Fault  
1011 Rupture and Fault Segmentation: Examples from the 17 August 1999 Izmit  
1012 Earthquake on the North Anatolian Fault, Turkey: Bulletin of the Seismological  
1013 Society of America, v. 92, p. 19–42, doi:10.1785/0120000808.

1014 Macdonald, R., Crossley, R., and Waterhouse, K.S., 1983, Karroo basalts of  
1015 southern Malawi and their regional petrogenetic significance: Mineralogical  
1016 Magazine, v. 47, p. 281–289, doi:10.1180/minmag.1983.047.344.02.

1017 Macey, P.H. et al., 2010, Mesoproterozoic geology of the Nampula Block, northern  
1018 Mozambique: Tracing fragments of Mesoproterozoic crust in the heart of  
1019 Gondwana: Precambrian Research, v. 182, p. 124–148,  
1020 doi:10.1016/j.precamres.2010.07.005.

1021 Machette, M.N., Personius, S.F., Nelson, A.R., Schwartz, D.P., and Lund, W.R.,  
1022 1991, The Wasatch fault zone, Utah—segmentation and history of Holocene  
1023 earthquakes: Journal of Structural Geology, v. 13, p. 137–149,  
1024 doi:10.1016/0191-8141(91)90062-N.

- 1025 Manda, B.W.C., Cawood, P.A., Spencer, C.J., Prave, T., Robinson, R., and Roberts,  
1026 N.M.W., 2019, Evolution of the Mozambique Belt in Malawi constrained by  
1027 granitoid U-Pb, Sm-Nd and Lu-Hf isotopic data: *Gondwana Research*, v. 68, p.  
1028 93–107, doi:10.1016/j.gr.2018.11.004.
- 1029 McConnell, R.B., 1967, The East African Rift System: *Nature*, v. 215, p. 578–581,  
1030 doi:10.1038/215578a0.
- 1031 McLeod, A.E., Dawers, N.H., and Underhill, J.R., 2008, The propagation and linkage  
1032 of normal faults: insights from the Strathspey-Brent-Statfjord fault array, northern  
1033 North Sea: *Basin Research*, v. 12, p. 263–284, doi:10.1111/j.1365-  
1034 2117.2000.00124.x.
- 1035 Mitchell, T.M., and Faulkner, D.R., 2009, The nature and origin of off-fault damage  
1036 surrounding strike-slip fault zones with a wide range of displacements: A field  
1037 study from the Atacama fault system, northern Chile: *Journal of Structural*  
1038 *Geology*, v. 31, p. 802–816, doi:10.1016/j.jsg.2009.05.002.
- 1039 Montési, L.G.J., 2013, Fabric development as the key for forming ductile shear  
1040 zones and enabling plate tectonics: *Journal of Structural Geology*, v. 50, p. 254–  
1041 266, doi:10.1016/j.jsg.2012.12.011.
- 1042 Morewood, N.C., and Roberts, G.P., 2000, The geometry, kinematics and rates of  
1043 deformation within an en echelon normal fault segment boundary, central Italy:  
1044 *Journal of Structural Geology*, v. 22, p. 1027–1047, doi:10.1016/S0191-  
1045 8141(00)00030-4.
- 1046 Morley, C.K., 2010, Stress re-orientation along zones of weak fabrics in rifts: An  
1047 explanation for pure extension in ‘oblique’ rift segments? *Earth and Planetary*  
1048 *Science Letters*, v. 297, p. 667–673, doi:10.1016/j.epsl.2010.07.022.
- 1049 Mortimer, E., Kirstein, L.A., Stuart, F.M., and Strecker, M.R., 2016, Spatio-temporal

1050 trends in normal-fault segmentation recorded by low-temperature  
1051 thermochronology: Livingstone fault scarp, Malawi Rift, East African Rift System:  
1052 Earth and Planetary Science Letters, v. 455, p. 62–72,  
1053 doi:10.1016/j.epsl.2016.08.040.

1054 Mortimer, E., Paton, D.A., Scholz, C.A., Strecker, M.R., and Blisniuk, P., 2007,  
1055 Orthogonal to oblique rifting: effect of rift basin orientation in the evolution of the  
1056 North basin, Malawi Rift, East Africa: Basin Research, v. 19, p. 393–407,  
1057 doi:10.1111/j.1365-2117.2007.00332.x.

1058 Muirhead, J.D., and Kattenhorn, S.A., 2018, Activation of preexisting transverse  
1059 structures in an evolving magmatic rift in East Africa: Journal of Structural  
1060 Geology, v. 106, p. 1–18, doi:10.1016/j.jsg.2017.11.004.

1061 Muirhead, J.D., Wright, L.J.M., and Scholz, C.A., 2019, Rift evolution in regions of  
1062 low magma input in East Africa: Earth and Planetary Science Letters, v. 506, p.  
1063 332–346, doi:10.1016/j.epsl.2018.11.004.

1064 Nicol, A., Childs, C., Walsh, J.J., Manzocchi, T., and Schöpfer, M.P.J., 2017,  
1065 Interactions and growth of faults in an outcrop-scale system: Geological Society,  
1066 London, Special Publications, v. 439, p. 23–39, doi:10.1144/SP439.9.

1067 Nicol, A., Walsh, J., Berryman, K., and Nodder, S., 2005, Growth of a normal fault by  
1068 the accumulation of slip over millions of years: Journal of Structural Geology, v.  
1069 27, p. 327–342, doi:10.1016/j.jsg.2004.09.002.

1070 Ord, D.M., Clemmey, H., and Leeder, M.R., 1988, Interaction between faulting and  
1071 sedimentation during Dinantian extension of the Solway basin, SW Scotland:  
1072 Journal - Geological Society (London), v. 145, p. 249–259,  
1073 doi:10.1144/gsjgs.145.2.0249.

1074 Peacock, D.C., and Sanderson, D., 1991, Displacements, segment linkage and

1075 relay ramps in normal fault zones: *Journal of Structural Geology*, v. 13, p. 721–  
1076 733, doi:10.1016/0191-8141(91)90033-F.

1077 Petersen, M.D. et al., 2015, The 2014 United States National Seismic Hazard Model:  
1078 *Earthquake Spectra*, v. 31, p. S1–S30, doi:10.1193/120814EQS210M.

1079 Philippon, M., Willingshofer, E., Sokoutis, D., Corti, G., Sani, F., Bonini, M., and  
1080 Cloetingh, S., 2015, Slip re-orientation in oblique rifts: *Geology*, v. 43, p. 147–  
1081 150, doi:10.1130/G36208.1.

1082 Phillips, T.B., Jackson, C.A.L., Bell, R.E., Duffy, O.B., and Fossen, H., 2016,  
1083 Reactivation of intrabasement structures during rifting: A case study from  
1084 offshore southern Norway: *Journal of Structural Geology*, v. 91, p. 54–73,  
1085 doi:10.1016/j.jsg.2016.08.008.

1086 Phillips, T.B., and McCaffrey, K.J.W., 2019, Terrane Boundary Reactivation, Barriers  
1087 to Lateral Fault Propagation and Reactivated Fabrics: Rifting Across the Median  
1088 Batholith Zone, Great South Basin, New Zealand: *Tectonics*, v. 38, p. 4027–  
1089 4053, doi:10.1029/2019TC005772.

1090 Poirier, J.P., 1980, Shear localization and shear instability in materials in the ductile  
1091 field: *Journal of Structural Geology*, v. 2, p. 135–142, doi:10.1016/0191-  
1092 8141(80)90043-7.

1093 Prater, W.T. et al., 2016, Strain Accomodation of Cenezoic Rifting in the Northern  
1094 Margin of the Shire Graben, Southern Malawi Rift: American Geophysical Union,  
1095 Fall Meeting Abstracts,.

1096 Roberts, E.M., Stevens, N.J., O'Connor, P.M., Dirks, P.H.G.M., Gottfried, M.D.,  
1097 Clyde, W.C., Armstrong, R.A., Kemp, A.I.S., and Hemming, S., 2012, Initiation  
1098 of the western branch of the East African Rift coeval with the eastern branch:  
1099 *Nature Geoscience*, v. 5, p. 289–294, doi:10.1038/ngeo1432.

1100 Robertson, E.A.M., Biggs, J., Cashman, K. V., Floyd, M.A., and Vye-Brown, C.,  
1101 2016, Influence of regional tectonics and pre-existing structures on the formation  
1102 of elliptical calderas in the Kenyan Rift: Geological Society Special Publication,  
1103 v. 420, p. 43–67, doi:10.1144/SP420.12.

1104 Rotevatn, A., Jackson, C.A.L., Tvedt, A.B.M., Bell, R.E., and Blækkan, I., 2019, How  
1105 do normal faults grow? Journal of Structural Geology, v. 125, p. 174–184,  
1106 doi:10.1016/j.jsg.2018.08.005.

1107 Rotevatn, A., Kristensen, T.B., Ksienzyk, A.K., Wemmer, K., Henstra, G.A.,  
1108 Midtkandal, I., Grundvåg, S.A., and Andresen, A., 2018, Structural Inheritance  
1109 and Rapid Rift-Length Establishment in a Multiphase Rift: The East Greenland  
1110 Rift System and its Caledonian Orogenic Ancestry: Tectonics, v. 37, p. 1858–  
1111 1875, doi:10.1029/2018TC005018.

1112 Samsu, A., Cruden, A.R., Micklethwaite, S., Grose, L., and Vollgger, S.A., 2020,  
1113 Scale matters: The influence of structural inheritance on fracture patterns:  
1114 Journal of Structural Geology, v. 130, p. 103896, doi:10.1016/j.jsg.2019.103896.

1115 Savage, H.M., and Brodsky, E.E., 2011, Collateral damage: Evolution with  
1116 displacement of fracture distribution and secondary fault strands in fault damage  
1117 zones: Journal of Geophysical Research, v. 116, p. B03405,  
1118 doi:10.1029/2010JB007665.

1119 Schlische, R.W., Young, S.S., Ackermann, R. V., and Gupta, A., 1996, Geometry  
1120 and scaling relations of a population of very small rift-related normal faults:  
1121 Geology, v. 24, p. 683–686, doi:10.1130/0091-  
1122 7613(1996)024<0683:GASROA>2.3.CO;2.

1123 Scholz, C.H., Dawers, N.H., Yu, J.Z., Anders, M.H., and Cowie, P.A., 1993, Fault  
1124 growth and fault scaling laws: preliminary results: Journal of Geophysical

- 1125 Research, v. 98, p. 951–961.
- 1126 Segall, P., and Pollard, D.D., 1980, Mechanics of discontinuous faults: Journal of  
1127 Geophysical Research: Solid Earth, v. 85, p. 4337–4350,  
1128 doi:10.1029/JB085iB08p04337.
- 1129 Senger, K., Buckley, S.J., Chevallier, L., Fagereng, Å., Galland, O., Kurz, T.H.,  
1130 Ogata, K., Planke, S., and Tveranger, J., 2015, Fracturing of doleritic intrusions  
1131 and associated contact zones: Implications for fluid flow in volcanic basins:  
1132 Journal of African Earth Sciences, v. 102, p. 70–85,  
1133 doi:10.1016/j.jafrearsci.2014.10.019.
- 1134 Shipton, Z.K., and Cowie, P.A., 2003, A conceptual model for the origin of fault  
1135 damage zone structures in high-porosity sandstone: Journal of Structural  
1136 Geology, v. 25, p. 333–344, doi:10.1016/S0191-8141(02)00037-8.
- 1137 Smith, M., and Mosley, P., 1993, Crustal heterogeneity and basement influence on  
1138 the development of the Kenya Rift, East Africa: Tectonics, v. 12, p. 591–606,  
1139 doi:10.1029/92TC01710.
- 1140 Stamps, D.S., Saria, E., and Kreemer, C., 2018, A Geodetic Strain Rate Model for  
1141 the East African Rift System: Scientific Reports, v. 8, p. 1–8,  
1142 doi:10.1038/s41598-017-19097-w.
- 1143 Stenvall, C.A., Fagereng, Å., and Diener, J.F.A., 2019, Weaker Than Weakest: On  
1144 the Strength of Shear Zones: Geophysical Research Letters, v. 46, p. 7404–  
1145 7413, doi:10.1029/2019GL083388.
- 1146 Tenthorey, E., and Cox, S.F., 2006, Cohesive strengthening of fault zones during the  
1147 interseismic period: An experimental study: Journal of Geophysical Research:  
1148 Solid Earth, v. 111, p. 1–14, doi:10.1029/2005JB004122.
- 1149 Torabi, A., and Berg, S.S., 2011, Scaling of fault attributes: A review: Marine and

1150 Petroleum Geology, v. 28, p. 1444–1460, doi:10.1016/j.marpetgeo.2011.04.003.

1151 Torabi, A., Johannessen, M.U., and Ellingsen, T.S.S., 2019, Fault Core Thickness:  
1152 Insights from Siliciclastic and Carbonate Rocks: Geofluids, v. 2019, p. 1–24,  
1153 doi:10.1155/2019/2918673.

1154 Tucker, G.E., McCoy, S.W., Whittaker, A.C., Roberts, G.P., Lancaster, S.T., and  
1155 Phillips, R., 2011, Geomorphic significance of postglacial bedrock scarps on  
1156 normal-fault footwalls: Journal of Geophysical Research: Earth Surface, v. 116,  
1157 p. 1–14, doi:10.1029/2010JF001861.

1158 Turcotte, D.L., and Schubert, G., 2002, Geodynamics: New York, Cambridge  
1159 University Press, 607 p.

1160 Valentini, A., Duross, C.B., Field, E.H., Gold, R.D., Briggs, R.W., Visini, F., and  
1161 Pace, B., 2019, Relaxing Segmentation on the Wasatch Fault Zone : Impact on  
1162 Seismic Hazard: v. XX, doi:10.1785/0120190088.

1163 Walker, R.T., Wegmann, K.W., Bayasgalan, A., Carson, R.J., Elliott, J., Fox, M.,  
1164 Nissen, E., Sloan, R.A., Williams, J.M., and Wright, E., 2017, The Egiin Davaa  
1165 prehistoric rupture, central Mongolia: a large magnitude normal faulting  
1166 earthquake on a reactivated fault with little cumulative slip located in a slowly  
1167 deforming intraplate setting: Geological Society, London, Special Publications,  
1168 v. 432, p. 187–212, doi:10.1144/SP432.4.

1169 Walsh, J.J., Bailey, W.R., Childs, C., Nicol, A., and Bonson, C.G., 2003, Formation of  
1170 segmented normal faults: A 3-D perspective: Journal of Structural Geology, v.  
1171 25, p. 1251–1262, doi:10.1016/S0191-8141(02)00161-X.

1172 Walsh, J.J., Nicol, A., and Childs, C., 2002, An alternative model for the growth of  
1173 faults: Journal of Structural Geology, v. 24, p. 1669–1675, doi:10.1016/S0191-  
1174 8141(01)00165-1.

1175 Walters, R.J. et al., 2018, Dual control of fault intersections on stop-start rupture in  
1176 the 2016 Central Italy seismic sequence: *Earth and Planetary Science Letters*,  
1177 v. 500, p. 1–14, doi:10.1016/j.epsl.2018.07.043.

1178 Wästeby, N., Skelton, A., Tollefsen, E., Andrén, M., Stockmann, G., Claesson  
1179 Liljedahl, L., Sturkell, E., and Mörth, M., 2014, Hydrochemical monitoring,  
1180 petrological observation, and geochemical modeling of fault healing after an  
1181 earthquake: *Journal of Geophysical Research: Solid Earth*, v. 119, p. 5727–  
1182 5740, doi:10.1002/2013JB010715.

1183 Watterson, J., 1975, Mechanism for the persistence of tectonic lineaments: *Nature*,  
1184 v. 253, p. 520–522, doi:10.1038/253520b0.

1185 Wedmore, L.N.J., Biggs, J., Williams, J.N., Fagereng, Å., Dulanya, Z., Mphepo, F.,  
1186 and Mdala, H., 2020, Active Fault Scarps in Southern Malawi and Their  
1187 Implications for the Distribution of Strain in Incipient Continental Rifts: *Tectonics*,  
1188 v. 39, doi:10.1029/2019TC005834.

1189 Wei, S. et al., 2011, Superficial simplicity of the 2010 El Mayor–Cucapah earthquake  
1190 of Baja California in Mexico: *Nature Geoscience*, v. 4, p. 615–618,  
1191 doi:10.1038/ngeo1213.

1192 Wesnousky, S.G., 2008, Displacement and geometrical characteristics of earthquake  
1193 surface ruptures: Issues and implications for seismic-hazard analysis and the  
1194 process of earthquake rupture: *Bulletin of the Seismological Society of America*,  
1195 v. 98, p. 1609–1632, doi:10.1785/0120070111.

1196 Wesnousky, S.G., 2006, Predicting the endpoints of earthquake ruptures: *Nature*, v.  
1197 444, p. 358–360, doi:10.1038/nature05275.

1198 Wessel, P., Smith, W.H.F., Scharroo, R., Luis, J., and Wobbe, F., 2013, Generic  
1199 Mapping Tools: Improved Version Released: *Eos, Transactions American*

1200 Geophysical Union, v. 94, p. 409–410, doi:10.1002/2013EO450001.

1201 Westerhof, A.P., Lehtonen, M.I., Mäkitie, H., Manninen, T., Pekkala, Y., Gustafsson,  
1202 B., and Tahon, A., 2008, The Tete-Chipata Belt: a new multiple terrane element  
1203 from western Mozambique and southern Zambia: Geological Survey of Finland  
1204 Special PAper, v. 48, p. 145–166.

1205 Wheeler, W.H., and Karson, J.A., 1989, Structure and kinematics of the Livingstone  
1206 Mountains border fault zone, Nyasa (Malawi) Rift, southwestern Tanzania:  
1207 Journal of African Earth Sciences (and the Middle East), v. 8, p. 393–413,  
1208 doi:10.1016/S0899-5362(89)80034-X.

1209 Whipp, P.S., Jackson, C.A.L., Gawthorpe, R.L., Dreyer, T., and Quinn, D., 2014,  
1210 Normal fault array evolution above a reactivated rift fabric; a subsurface  
1211 example from the northern Horda Platform, Norwegian North Sea: Basin  
1212 Research, v. 26, p. 523–549, doi:10.1111/bre.12050.

1213 Willemse, E.J.M., 1997, Segmented normal faults: Correspondence between three-  
1214 dimensional mechanical models and field data: Journal of Geophysical  
1215 Research: Solid Earth, v. 102, p. 675–692, doi:10.1029/96jb01651.

1216 Willemse, E.J.M., Pollard, D.D., and Aydin, A., 1996, Three-dimensional analyses of  
1217 slip distributions on normal fault arrays with consequences for fault scaling:  
1218 Journal of Structural Geology, v. 18, p. 295–309, doi:10.1016/S0191-  
1219 8141(96)80051-4.

1220 Williams, J.N., Fagereng, Å., Wedmore, L.N.J., Biggs, J., Mphepo, F., Dulanya, Z.,  
1221 Mdala, H., and Blenkinsop, T., 2019, How Do Variably Striking Faults Reactivate  
1222 During Rifting? Insights From Southern Malawi: Geochemistry, Geophysics,  
1223 Geosystems, p. 3588–3607, doi:10.1029/2019gc008219.

1224 Williams, J.N., Toy, V.G., Smith, S.A.F., and Boulton, C., 2017, Fracturing, fluid-rock

1225 interaction and mineralisation during the seismic cycle along the Alpine Fault:  
1226 Journal of Structural Geology, v. 103, p. 151–166,  
1227 doi:10.1016/j.jsg.2017.09.011.

1228 Wilson, J., Chester, J., and Chester, F., 2003, Microfracture analysis of fault  
1229 growth and wear processes, Punchbowl Fault, San Andreas system, California:  
1230 Journal of Structural Geology, v. 25, p. 1855–1873, doi:10.1016/S0191-  
1231 8141(03)00036-1.

1232 Woolley, A.R., 1987, Lithosphere metasomatism and the petrogenesis of the Chilwa  
1233 Province of alkaline igneous rocks and carbonatites, Malawi: Journal of African  
1234 Earth Sciences, v. 6, p. 891–898, doi:10.1016/0899-5362(87)90048-0.

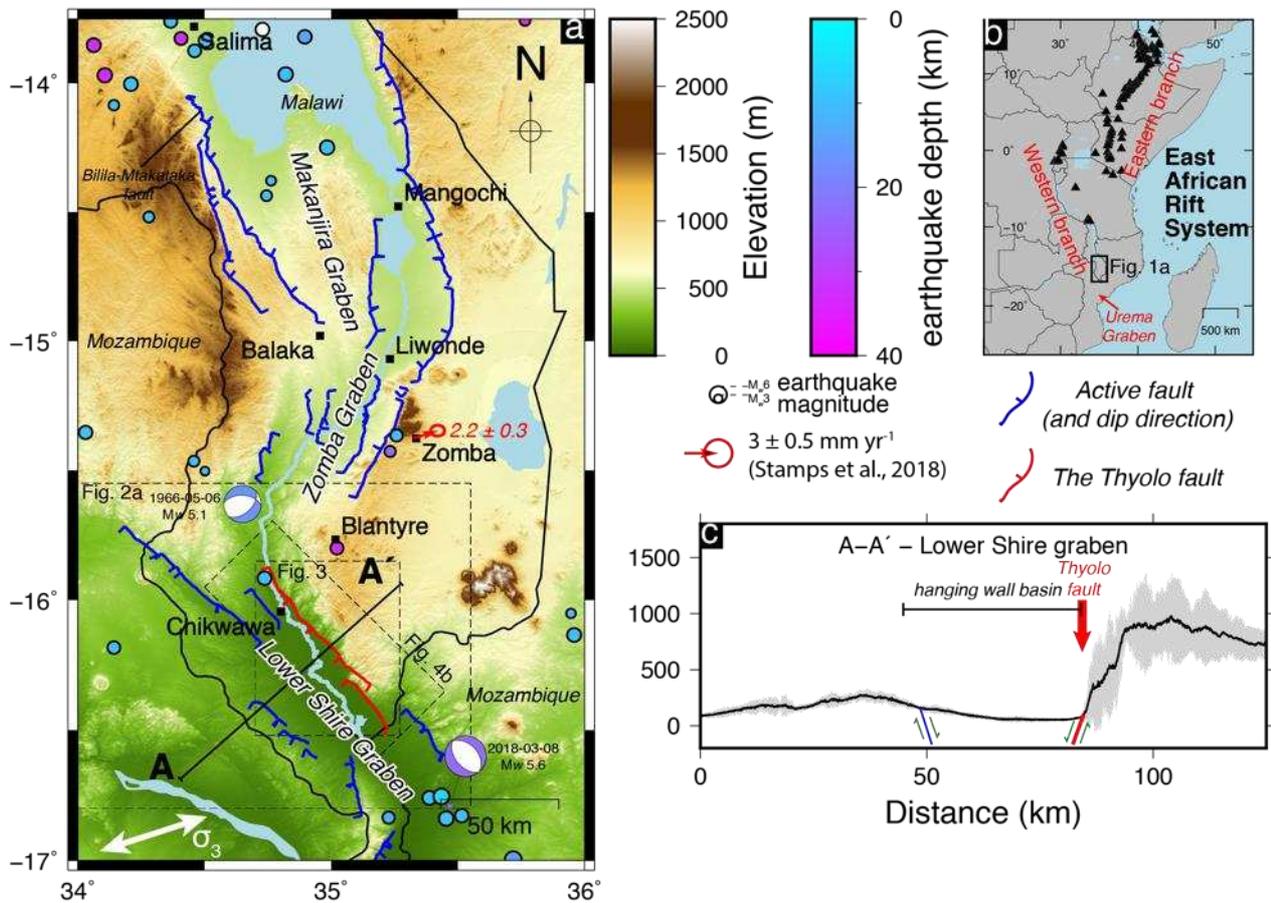
1235 Woolley, A.R., Bevan, J.C., and Elliott, C.J., 1979, The Karroo dolerites of southern  
1236 Malawi and their regional geochemical implications: Mineralogical Magazine, v.  
1237 43, p. 487–495, doi:10.1180/minmag.1979.043.328.08.

1238 Worthington, R.P., and Walsh, J.J., 2017, Timing, growth and structure of a  
1239 reactivated basin-bounding fault: Geological Society, London, Special  
1240 Publications, v. 439, p. 511–531, doi:10.1144/SP439.14.

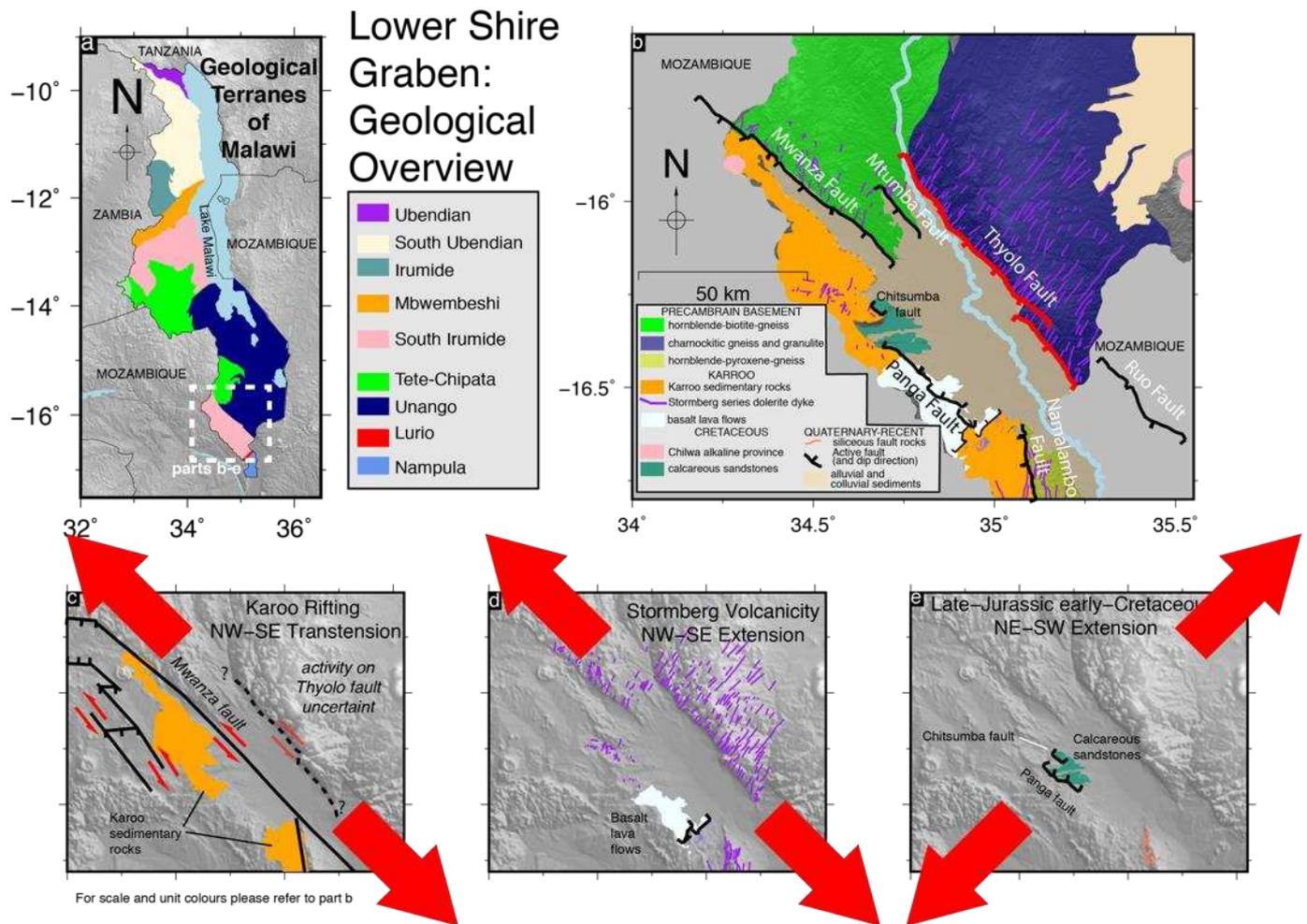
1241 Zangerl, C., Loew, S., and Eberhardt, E., 2006, Structure, geometry and formation of  
1242 brittle discontinuities in anisotropic crystalline rocks of the Central Gotthard  
1243 Massif, Switzerland: *Eclogae Geologicae Helvetiae*, v. 99, p. 271–290,  
1244 doi:10.1007/s00015-006-1190-0.

1245 Zhang, P., Slemmons, D.B., and Mao, F., 1991, Geometric pattern, rupture  
1246 termination and fault segmentation of the Dixie Valley-Pleasant Valley active  
1247 normal fault system, Nevada, U.S.A.: Journal of Structural Geology, v. 13, p.  
1248 165–176, doi:10.1016/0191-8141(91)90064-P.

1249

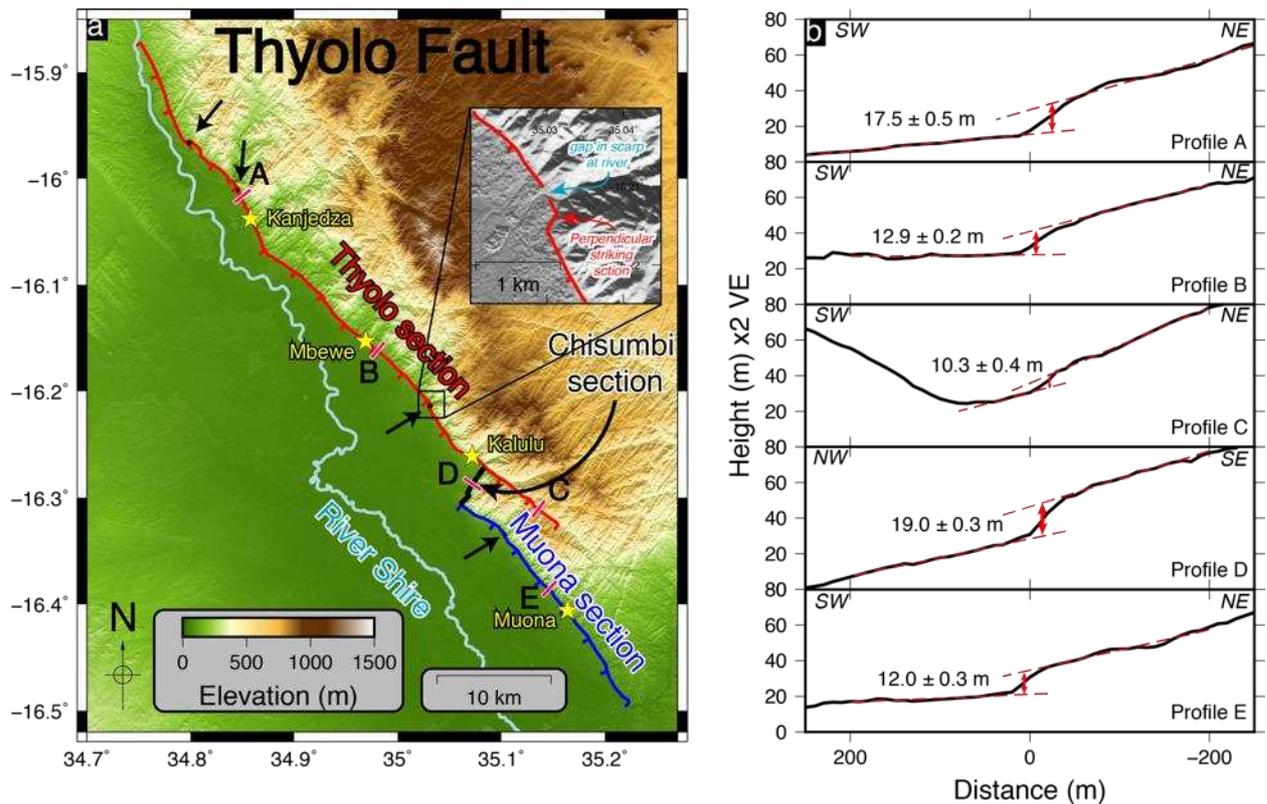


1250 Figure 1. The location and tectonic context of the Lower Shire Graben. (a) The  
 1251 southern Malawi rift system with known active fault scarps in blue and the Thyolo  
 1252 fault highlighted in red. Also shown is the GPS vector from a station in Zomba,  
 1253 National Earthquake Information Centre earthquake locations from 1971-2018  
 1254 (circles coloured by depth), and focal mechanisms for the two largest events in the  
 1255 region, a M<sub>w</sub>5.1 earthquake in 1966 (from Craig et al., 2011) and the CMT solution  
 1256 for the 2018 Nsanje earthquake (M<sub>w</sub>5.6). Extension direction ( $\sigma_3$ ; 072°) is from a  
 1257 moment tensor inversion in Williams et al. (2019) (b) The location of the southern  
 1258 Malawi rift system within the East African Rift. Triangles indicate Holocene active  
 1259 volcanoes. (c) Swath topographic cross section across the Lower Shire Graben  
 1260 extracted from TanDEM-X data. Black line is the median elevation with the grey  
 1261 shading the maximum and minimum elevation 10 km either side of profile A-A'  
 1262 indicated in part a.



1263 Figure 2. Geological overview of the Lower Shire Graben. (a) Geological terranes  
 1264 within Malawi (Fullgraf et al., *in press*). (b) Simplified geological map of the Lower  
 1265 Shire Graben adapted from Hapgood 1963. (c) Structures related to NW-SE Karoo-  
 1266 age amagmatic transtension. Note the activity of the Thyolo fault during this period is  
 1267 uncertain. (d) Dykes and normal faults associated with NW-SE magmatic rifting in  
 1268 the late Karoo period. (e) Normal faults and sedimentary deposits related to NE-SW  
 1269 rifting during the Late-Jurassic to early-Cretaceous.

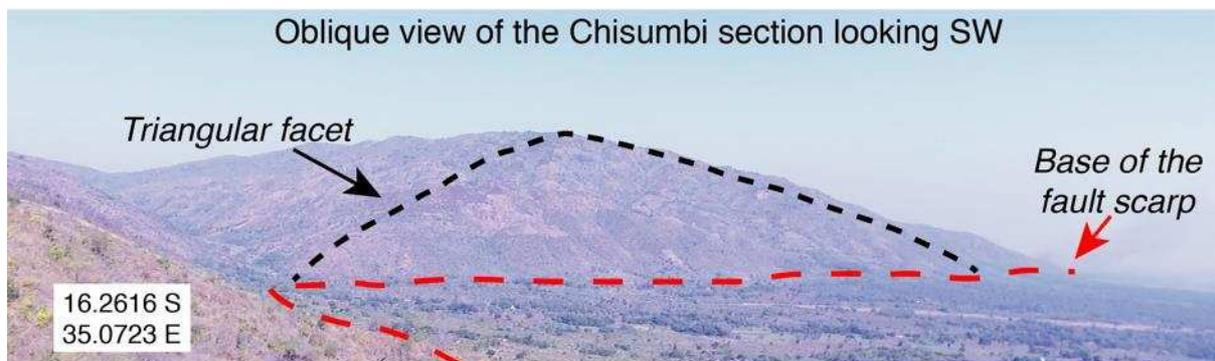
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1271

1272 Figure 3 (a) TanDEM-X digital elevation model of the Thyolo fault showing both the  
 1273 Thyolo (red) and Muona (blue) sections. The fault sections oriented at  $\sim 90^\circ$  to the  
 1274 main strike are indicated in black with sections visible at this scale identified by black  
 1275 arrows. Yellow stars indicate the locations of field studies reported in this paper. Pink  
 1276 rectangles indicate are the locations and orientation of illustrative topographic  
 1277 profiles extracted perpendicular to the fault scarp and shown in part b. (b) Example  
 1278 topographic profiles extracted perpendicular the fault scarp. All profiles are plotted  
 1279 with the footwall on the right-hand side (profile orientation is indicated in the top of  
 1280 each panel). Note profile D is located along the Chisumbi section where the strike is  
 1281 oriented  $\sim 90^\circ$  to the strike of the main fault sections.

1282

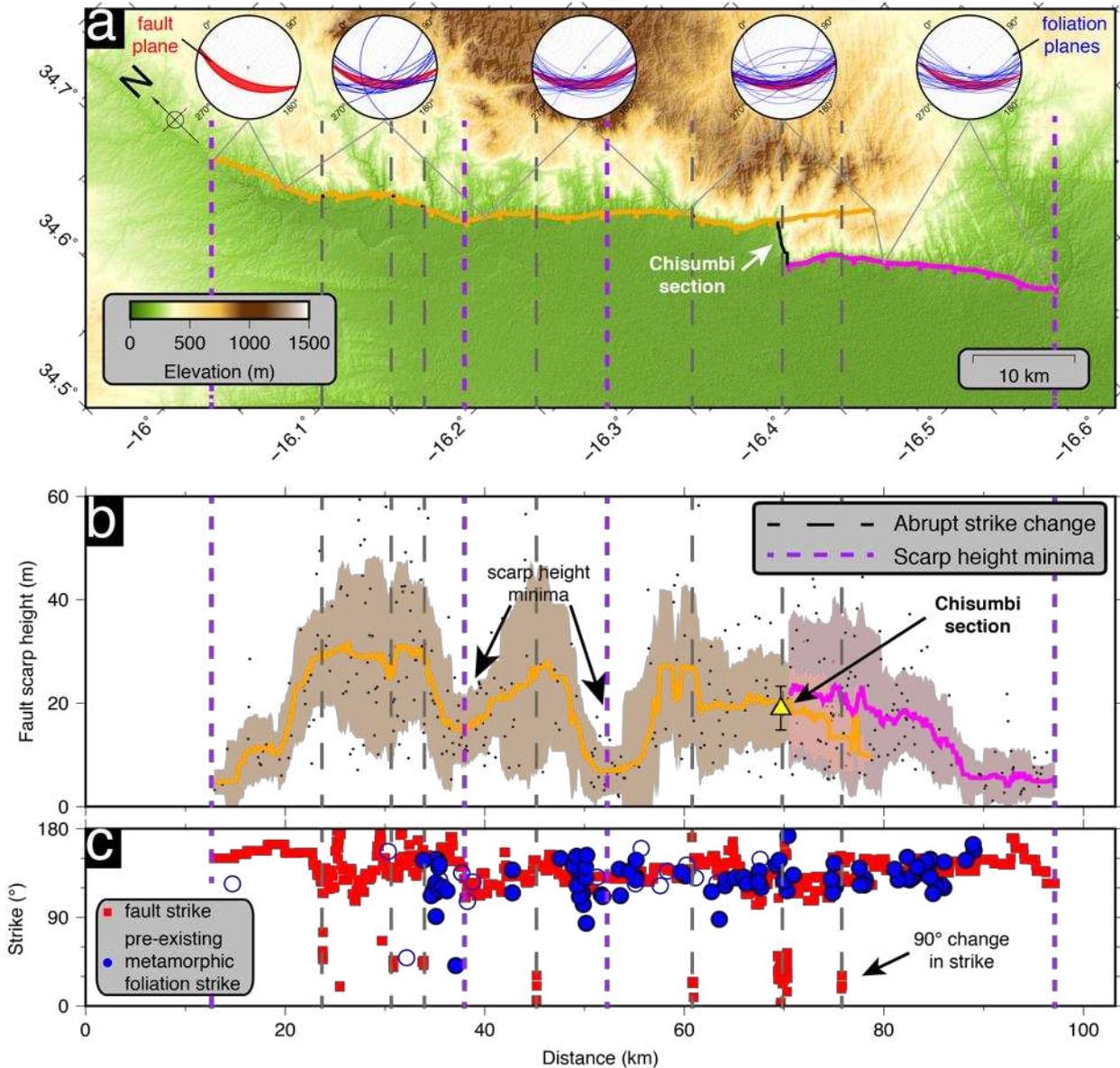


1283

1284 Figure 4. Field photos of the Thyolo fault. (a) An oblique view of the fault scarp along  
 1285 the Thyolo fault taken using a drone, showing an approximately 15 m high scarp.  
 1286 See the video available in the supplementary material for additional views of the  
 1287 scarp at this location. (b) An oblique view of the Chisumbi section taken using a  
 1288 drone, showing one of the triangular facets that are common along south eastern  
 1289 end of the fault. This section of the fault strikes perpendicular to the main section of  
 1290 the fault, which is just visible in the bottom left of the photo.

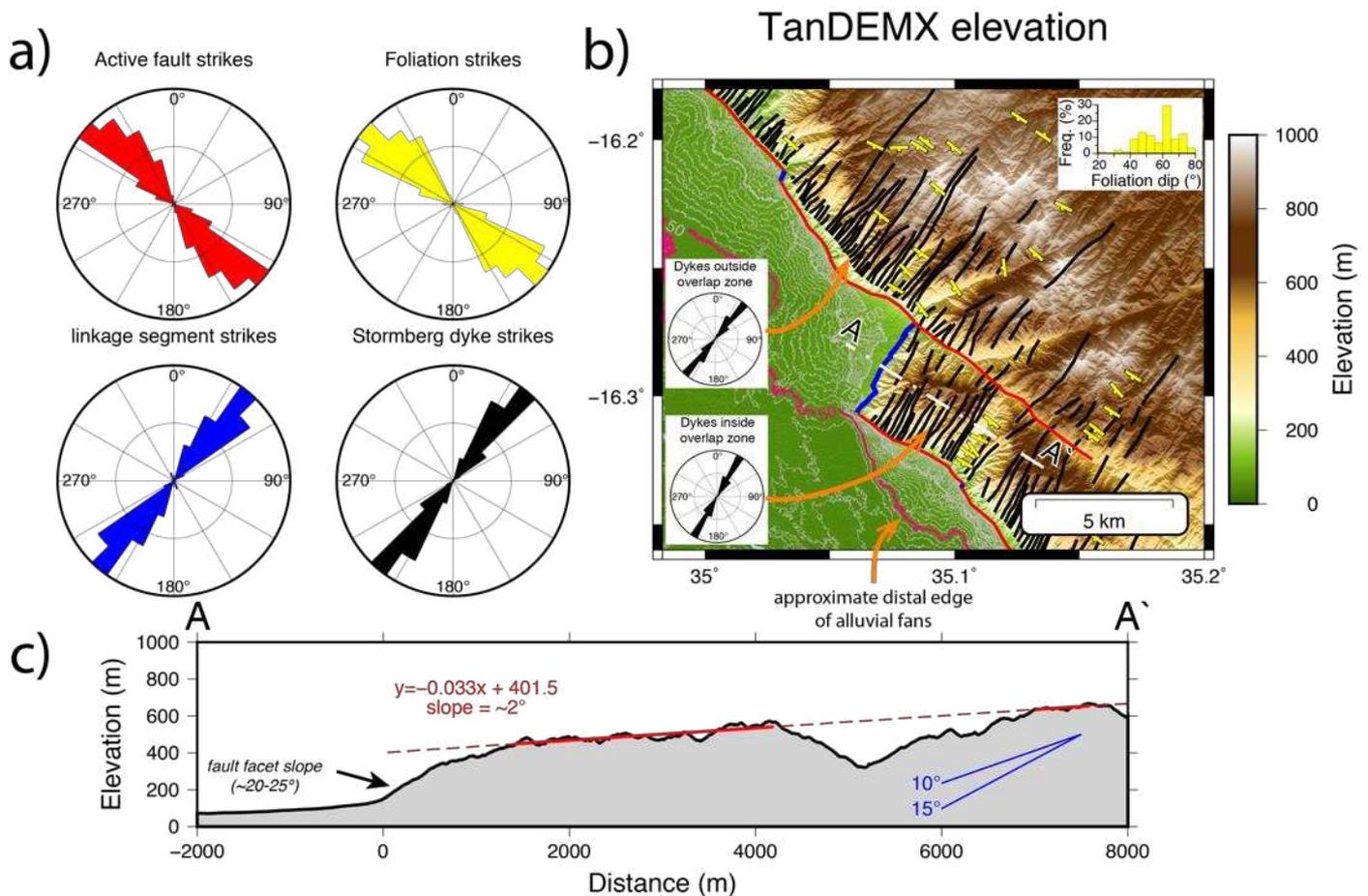
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# The Thyolo fault scarp and segmentation



1293 Figure 5. Thyolo fault scarp height and segmentation. (a) A rotated view of the  
 1294 Thyolo fault showing different indicators of fault segmentation. Inset equal angle,  
 1295 lower hemisphere stereonet plots are rotated into the same view as the underlying map.  
 1296 Red ellipses show the mean fault orientation measured every 20 km, with a dip  
 1297 value plotted between 45°-60°, and the blue lines show foliation orientations. (b) The  
 1298 height of the Thyolo fault scarp as a function of distance from the NW to the SE  
 1299 along the fault. (c) The strike of the Thyolo fault (measured every 50 m) and foliation

1300 strike measurements (Habgood et al., 1973) as a function of distance from NW to SE  
1301 along the fault. Open blue circles represent foliation measurements that did not give  
1302 details of the dip of the foliation on the original geological map (Habgood et al.,  
1303 1973). Scarp height in b was measured using topographic profiles, perpendicular to  
1304 the scarp, extracted every 100 m along strike. Black dots are the individual  
1305 measurements with the solid coloured lines the 5 km moving median of these  
1306 measurements. The shaded areas represents the  $1\sigma$  error bars. Red line is the  
1307 Thyolo section, blue line is the Muona section. The yellow triangle (with  $1\sigma$  error  
1308 bars) is the scarp height along the ~4 km linking segment.



1309 Figure 6. The Chisumbi linkage section between the Thyolo and Muona sections. (a)

1310 Rose diagrams of the orientation of surface traces of the different structures along

1311 the Thyolo fault. Active faults include the Thyolo and Muona fault sections as

1312 indicated on the map. The fault sections and dykes were divided into 50 m long

1313 sections before calculating the strike of each section. Linkage segments only include

1314 the sections of fault that strike approximately perpendicular to the Thyolo and Muona

1315 sections. Foliation orientations and Stormberg dykes were digitised from Habgood et

1316 al. (1973). (b) TanDEM-X DEM of the Chisumbi linkage section between the Thyolo

1317 and Muona sections. Dykes are indicated with black lines, foliation orientation and

1318 dip direction with yellow lines and ticks, faults with red lines and sections of the fault

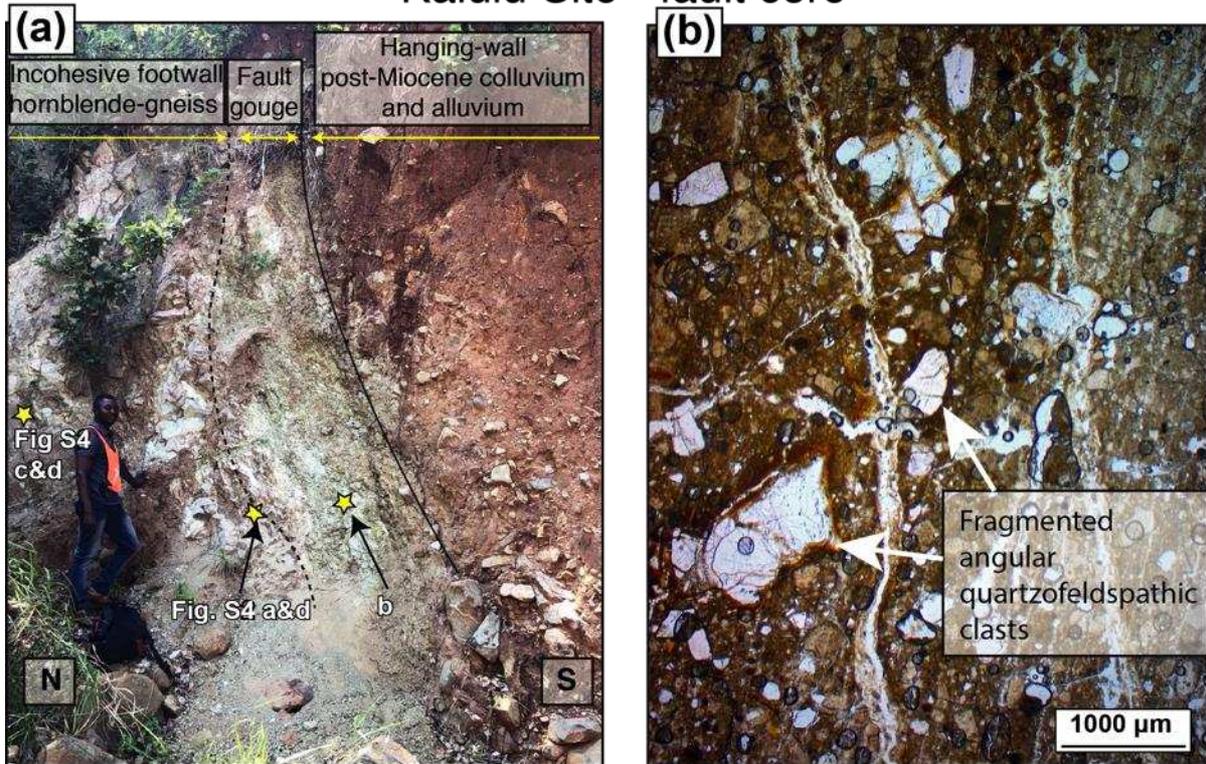
1319 that strike perpendicular to the main fault with blue lines. Grey contour lines are 2.5

1320 m apart, with the 50 m contour, which marks the approximate distal edge of alluvial

1321 fan complexes originating from footwall catchments, marked in pink. The inset

1322 histogram shows the dip of foliation measurements (Habgood et al., 1973). The inset  
1323 rose diagrams show the orientation of dykes located inside and outside of the zone  
1324 where the Thyolo and Muona sections overlap. (c) Swath topographic extracted  
1325 along the transect A-A` shown in part b. The mean topography 1 km either side of  
1326 the transect is plotted. The red line is a linear best fit to the slope of the topography  
1327 within the portions of the solid red line. The dashed portions are not used as they  
1328 have been affected by erosion due to river incision or include the fault scarp and fault  
1329 facet slope. Angles which are the normal range of breached relay ramp dips  
1330 (according to Fossen and Rotevatn, 2016) are plotted for comparison.  
1331

## Kalulu Site - fault core



1332

1333 Figure 7 (a) Fault zone exposure at Kalulu showing juxtaposition of hanging wall

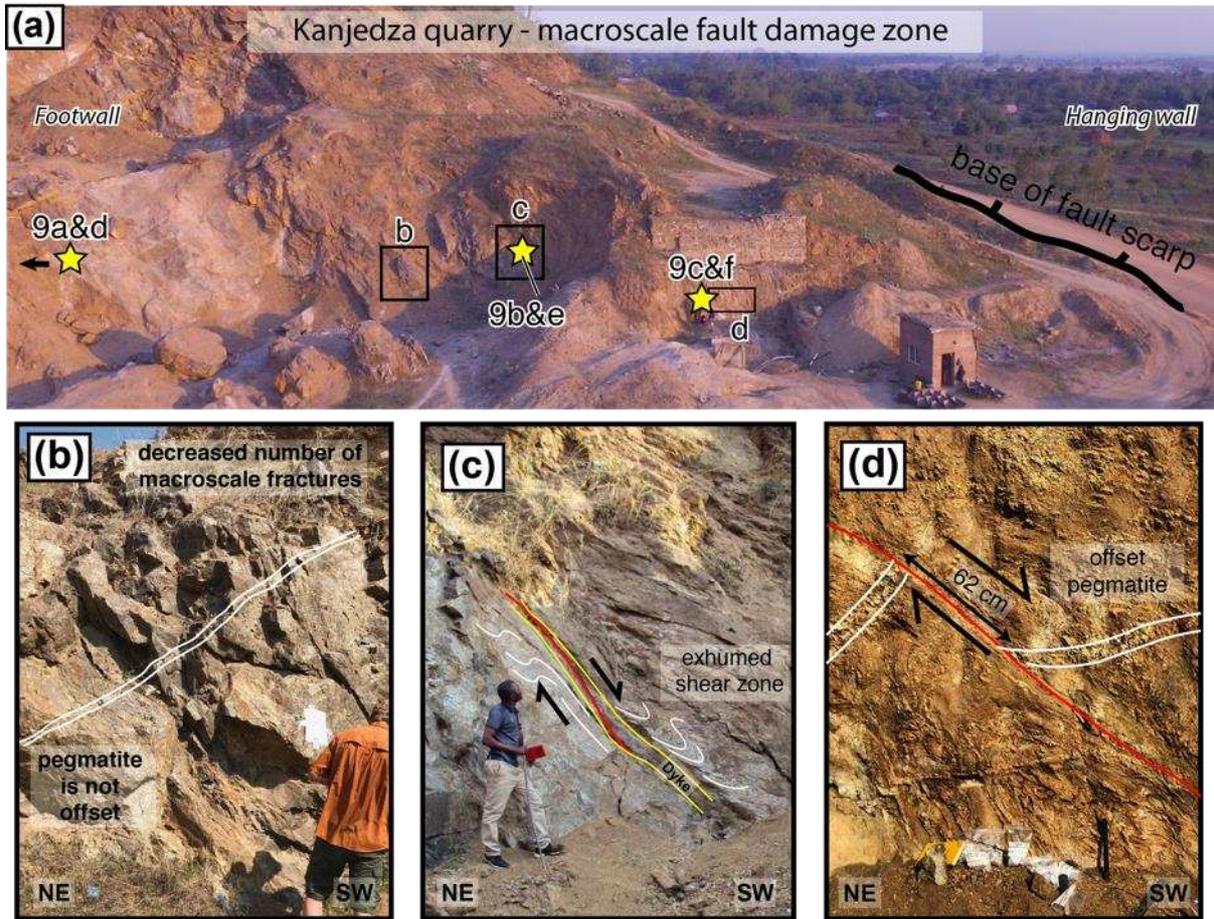
1334 sediments and footwall basement across a 0.7 m unit of fault gouge. Locations of

1335 samples used for photomicrographs in (b-f) shown by yellow stars. (b)

1336 photomicrograph of gouge with fractured quartz clasts and clay-rich brown matrix in

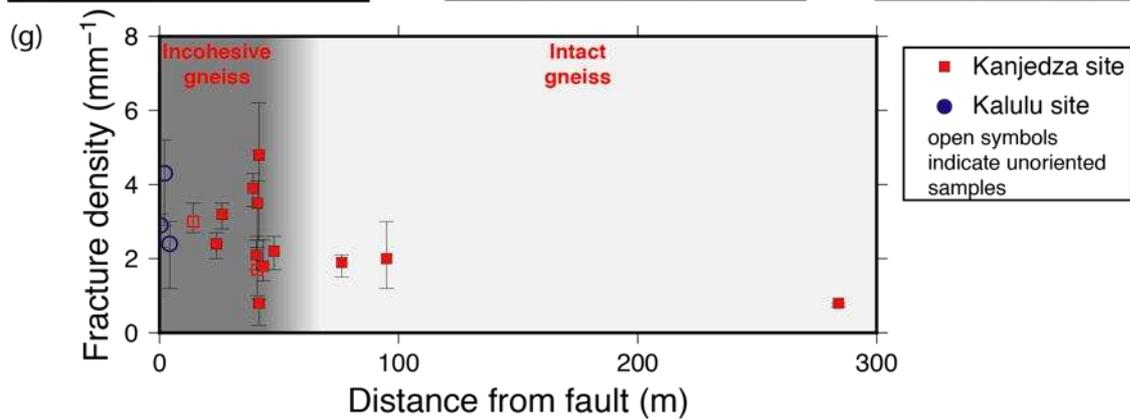
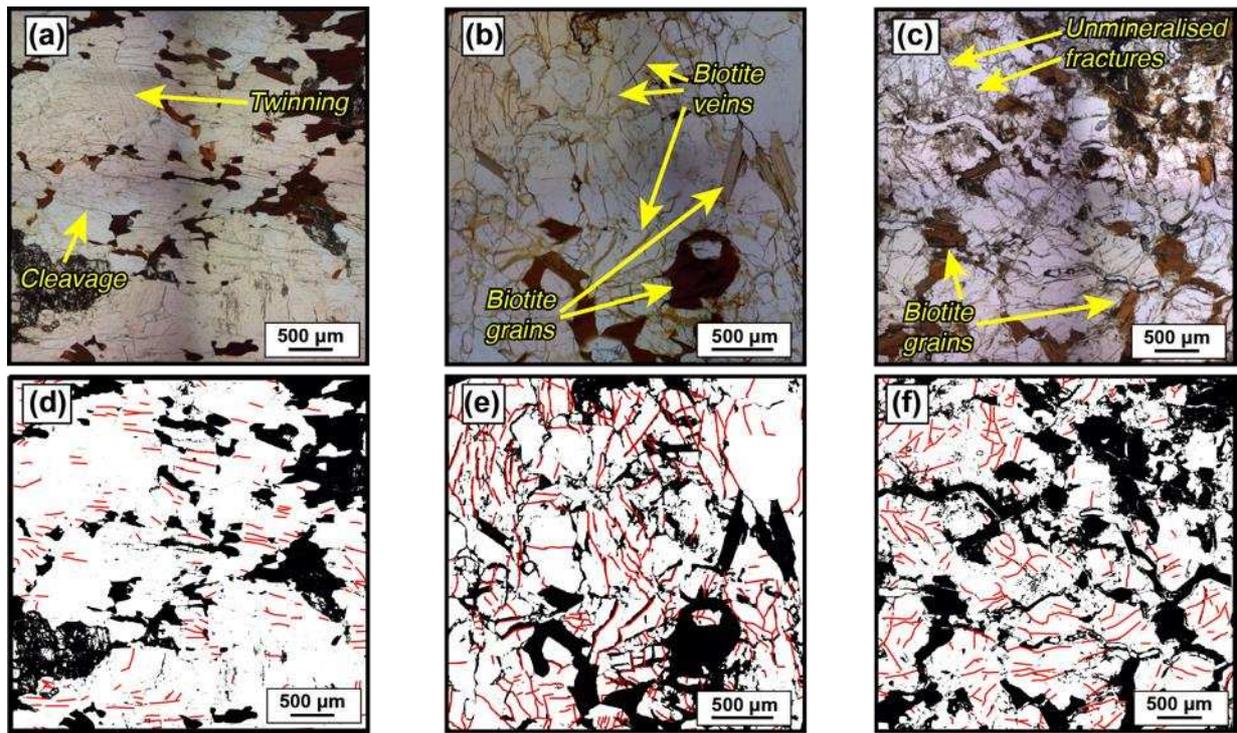
1337 plane polarised light (PPL) in sample from fault contact.

1338



1340  
 1341 Figure 8. Macroscale fault damage zone at the Kanjedza site along the Thyolo fault.

1342 (a) A perspective view of the exposed fault zone indicating the location of sample  
 1343 macroscale photos shown in parts b-d. Locations of microscale observations shown  
 1344 in Figure 9 are indicated with yellow stars. (b) Outcrop from outside the macroscale  
 1345 fault damage zone, note the lack of fracturing within the basement rock when  
 1346 compared with c and d. (c) Outcrop within the fault damage zone showing an  
 1347 exhumed shear zone and dyke. We infer that the shear zone had a reverse sense of  
 1348 shear as we can observe the same ductile structures on both the hanging wall and  
 1349 footwall sides of the fault. The dyke edge has been reactivated in a normal sense  
 1350 and acts as a minor slip surface with the same NW-SE strike as the main fault. (d)  
 1351 Offset pegmatite within the footwall damage zone.



1353

1354 Figure 9. Microscale fault damage zone at Kanjedza Quarry. Photomicrograph of

1355 samples (a) from outside the fault zone; (b) adjacent to a minor footwall slip surface

1356 (Figure 8c); and (c) within the fault damage zone. (d-f) annotated photomicrographs

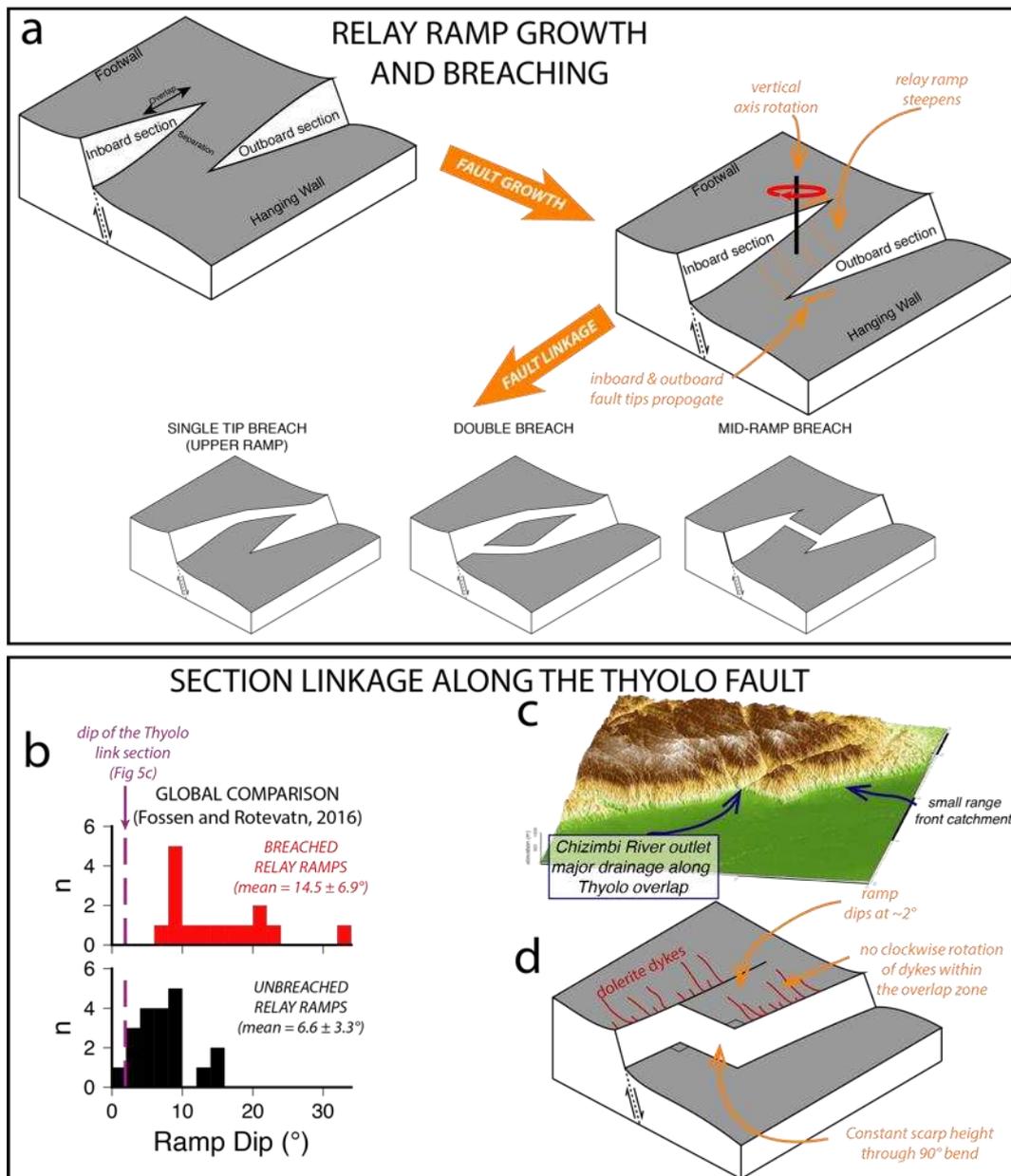
1357 of parts b-c showing the fractures (red lines) identified in each sample. (g)

1358 Compilation of fracture density plotted against distance from the fault for the

1359 Kanjedza and Kalulu sites along the Thyolo fault. The division between intact and

1360 incohesive gneiss is based on field observations (Figure 8).

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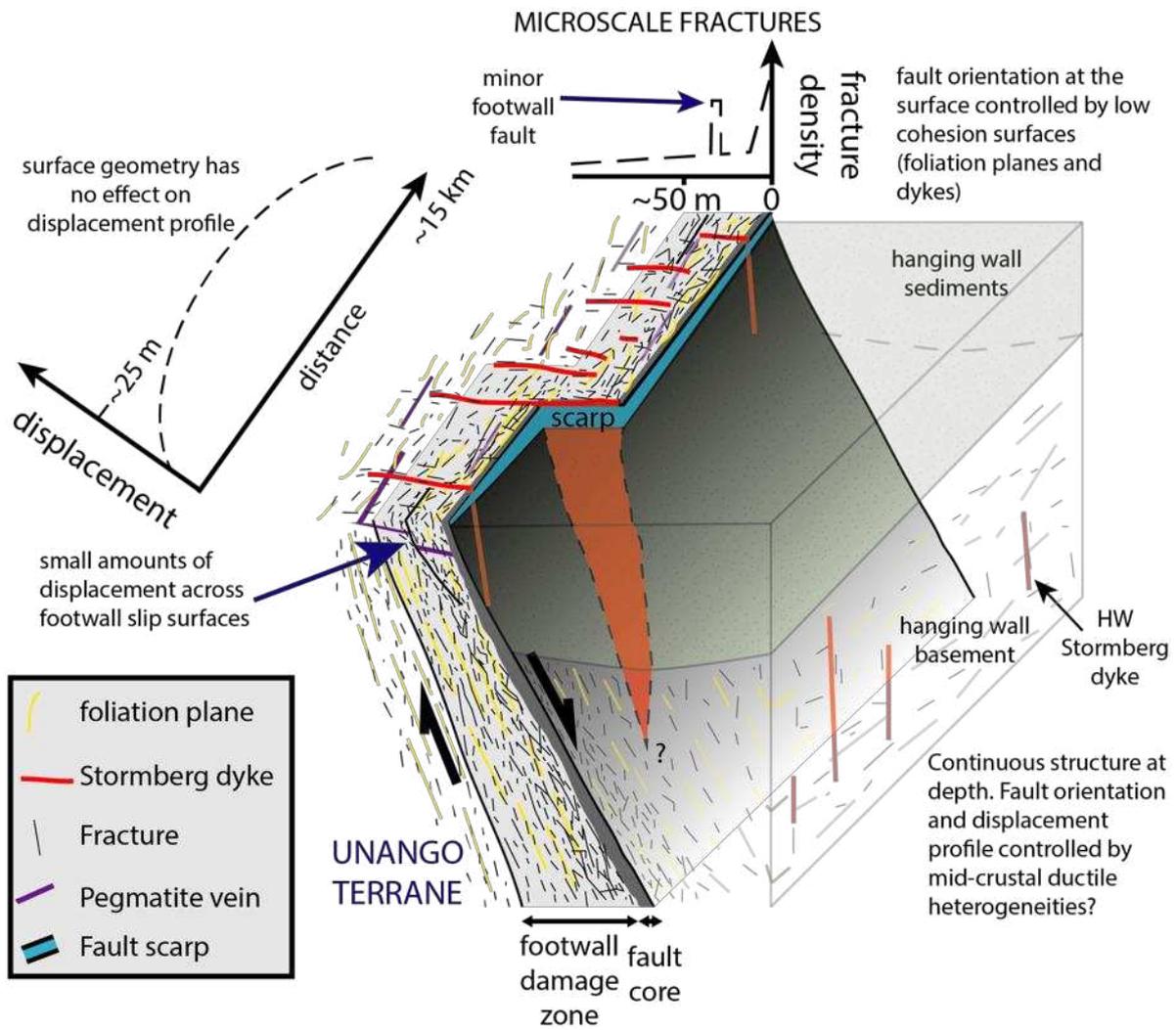
Figure 10. A comparison of relay ramp morphology and the linkage section between the Thyolo and Muona sections. (a) A summary of relay ramp growth and breaching (adapted from Fossen and Rotevatn, 2016). (b) The dip of relay ramp dips from a global compilation of breached and unbreached relay ramps (Fossen and Rotevatn, 2016). The dip of the topography in the section between the Thyolo and Muona sections is indicated with the purple dashed line. (c) A 3d view of the link section between the Thyolo and Muona sections showing the prominent drainage channels including the range front catchments that are predominate in the region and the

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1371 triangular facets along the Chisumbi section. (d) A conceptual view of the way the

1372 Thyolo fault has linked between the Thyolo and Muona sections.

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1376 Figure 11. A conceptual model of the reactivation of the Thyolo fault towards the  
 1377 edge of the Unango Terrane boundary. Shallow structures, including the 90° bend  
 1378 and the fault damage zone are controlled by the pre-existing metamorphic foliation  
 1379 and dykes. In contrast, the displacement profile is not affected by these shallow  
 1380 structures, instead, we suggest that a deeper more continuous structure is  
 1381 responsible for the segmentation of the fault observed in the displacement profile.  
 1382 This deeper structure may be associated with the edge of the Unango Terrane.