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31 **Controls of basement fabric on rift coupling and development of normal fault**  
32 **geometries: Insights from the Rukwa - North Malawi Rift**  
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71 **Highlights**

- 72 • To the SW, newfound strike-slip fault links the Rukwa and North Malawi Rift (RNMRS)
- 73 • To the NE, RNMRS border faults, intervening faults and volcanic centers are colinear
- 74 • RNMRS border faults and transfer structures align with pre-existing basement fabrics
- 75 • Basement fabrics guide the development of normal fault geometries and rift bifurcation
- 76 • Basement fabrics facilitate the coupling of the RMRS border faults and transfer structures

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78

79 **ABSTRACT**

80 The Rukwa Rift and North Malawi Rift Segments (RNMRS) both define a major rift-oblique  
81 segment of the East African Rift System (EARS), and although the two young rifts show colinear  
82 approaching geometries, they are often regarded as discrete rifts due to the presence of the  
83 intervening Mbozi Block uplift located in-between. This problem has been complicated by the  
84 dominance of the Rungwe volcanic features along the northeastern boundary of the Mbozi Block  
85 and lack of distinct normal faults along the southwestern boundary of the block. Here, we  
86 investigate the coupling of discrete rift segments during the onset of continental rifting, modulated  
87 by the control of pre-existing basement fabrics on the development of the border fault geometries  
88 and linkage across the intra-rift transfer zone. We utilized the Shuttle Radar Topography Mission  
89 Digital Elevation Models (SRTM-DEM) to investigate the morphological architecture of the rift  
90 domains; and aeromagnetic data and SRTM-DEM to assess the relationships between the rift  
91 structures and the pre-existing basement fabric (in plan-view). Our results show that the present-  
92 day morphology of the RNMRS is characterized by along-rift alternation of rift shoulder polarity,  
93 characteristic of coupled rift segments. Careful interpretation of filtered aeromagnetic maps along

94 the northeastern and southwestern boundaries of the RNMRS reveal striking alignment of the rift-  
95 bounding faults with colinear NW-SE-trending pre-existing basement fabrics. We find that rift  
96 coupling along the northeastern boundary of the Mbozi Block transfer zone is accommodated by  
97 magmatism utilizing pre-existing fault systems, whereas, coupling along the southwestern  
98 boundary is accommodated by a new-found dextral strike-slip fault. Additionally, we show how  
99 the configuration of the pre-existing basement fabrics may influence the development of rectilinear  
100 or curvilinear normal fault geometries (plan-view) along the rifts, and the formation of basin-scale  
101 rift bifurcation around basement inter-rift transfer zones. In summary, we suggest that the  
102 structural continuation of the boundary faults along the RNMRS, and their alignment with colinear  
103 basement fabrics demonstrate the influence of structural inheritance on the coupling and  
104 amalgamation of approaching rift segments.

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## 117 **1. INTRODUCTION**

118 Pre-existing basement fabrics are often major facilitators of continental rifting environments.  
119 Mechanically, they represent areas of structural weakness that can become reactivated and allow  
120 rifts to propagate preferentially along them (e.g., Daly et al., 1989). Several studies have  
121 documented the relationships between rift faults and the pre-existing basement fabrics (e.g.,  
122 Wheeler and Karson, 1989; Kinabo et al., 2007, 2008; Taylor et al., 2011; Phillips et al., 2016;  
123 Kolawole et al., 2018; Siuda et al., 2018). Further, recent studies have assessed the 3-dimensional  
124 relationship between pre-existing basement thrusts and intra-rift normal faults, revealing the  
125 control of the pre-existing basement structures on the nucleation and strain distribution along the  
126 normal faults (e.g., Collanega et al., 2018). In the Cenozoic East African Rift System (EARS),  
127 which is divided into an Eastern, a Western and a Southwestern Branch (Fig. 1A), several zones  
128 of well-developed basement fabric influence rifting. One of the best recently-documented  
129 examples highlighting the influence of the Precambrian basement shear zones on rifting in eastern  
130 Africa is the role of the Mwembeshi Shear Zone on the development of the Luangwa Rift (Fig.  
131 1A; Sarafian et al., 2018). It was demonstrated that the Mwembeshi Shear Zone acted as  
132 lithospheric conduit for fluids to migrate up the lithosphere, thus facilitating the weakening and  
133 subsequent initiation of the Luangwa rift in the Permo-Triassic.

134         However, the relationship between rift segments along the western branch of the EARS  
135 and the Precambrian shear zones is rather complex and warrants detailed and careful examination.  
136 For example, the Precambrian NW-trending Aswa shear zone resulted in the termination (rather  
137 than facilitation) of the northeastward propagation of the Albertine-Rhino graben which represents  
138 the northern-most segment of the Western Branch (Katumwehe et al., 2015) (Fig. 1A). On a basin  
139 scale, previous studies have also shown that pre-existing basement shear zones can influence the

140 localization of fault development (e.g., Phillips et al., 2016; Kolawole et al., 2018), and in fact  
141 control fault segmentation and across-basin strain transfer at later stages of rift development (e.g.,  
142 Muirhead and Kattenhorn, 2018).

143         The border faults along large continental rift systems, e.g., the EARS, are typically ~100  
144 km long (e.g., Foster et al., 1997; Lao-Davila et al., 2015), and the development of such large  
145 normal faults with complex segment linkage styles are yet to be fully understood (e.g., Fossen and  
146 Rotevatn, 2016; Gawthorpe et al., 2003; Rotevatn et al., 2018). However, since the interactions  
147 between the large normal faults within juvenile extensional tectonic settings lead to the systematic  
148 coupling of rift segments across transfer zones (e.g., Corti, 2012), border fault segmentation,  
149 geometries and continuity between rift segments can provide insight into the larger process of  
150 coupling between the segments of a rift system.

151         In this study, we focus on the Rukwa-North Malawi segment of the EARS, which is a major  
152 rift-oblique segment of the rift system and serves as the central segment of the system. For  
153 simplicity, we here-in refer to the Rukwa - Northern Malawi Rift segment of the East African Rift  
154 as the “RNMRS”. This segment is composed of the Rukwa Rift basin, the North Malawi Rift basin  
155 and the Mbozi Block which represents the accommodation zone between the two rifts (Fig. 1B).  
156 We address the longstanding question of the role of long-lived pre-existing basement structures in  
157 the development of the trends and geometries of rift-bounding faults, leading to subsequent  
158 coupling of individual rift segments during the onset of continental rifting. We demonstrate that  
159 there is continuous structural connectivity along the boundaries of the RNMRS, modulated by  
160 reactivation of the Precambrian metamorphic fabrics, and show that the characteristic plan-view  
161 geometries of the rift-bounding faults are modulated by the configuration of the basement fabric.  
162

## 163 2. GEOLOGIC SETTING

### 164 2.1. *The Precambrian Domains*

165 The Rukwa-North Malawi Rift Segment is located within the NW-trending Paleoproterozoic  
166 Ubendian orogenic belt which is sandwiched between the Archean Tanzanian craton in the  
167 northeast and the Bangweulu cratonic block to the southwest (Figs. 2A-B; Fritz et al., 2013). The  
168 Ubendian Belt is composed of different Precambrian terranes bounded by steep shear zones  
169 (Delvaux et al., 2012). These terranes contain granulite-facies metamorphic rocks (2100-2025  
170 Ma), amphibolite-facies metamorphic rocks and granitoids (1960-1800 Ma) that have undergone  
171 dextral strike-slip shearing and granitic plutons (1090-1120 Ma), (Fritz et al., 2013). The  
172 Paleoproterozoic Usagaran orogenic belt that extends NE-SW perpendicular to the Ubendian  
173 orogenic belt in southern Tanzania, is composed of eclogites (~2000 Ma), volcano-sedimentary  
174 cover with some low-grade metamorphism (~1920 Ma), and granitoids and granitoid gneisses  
175 (1900-1730 Ma) (Fritz et al., 2013). The Usagaran and Ubendian orogenic belts resulted from  
176 collision with the Tanzania craton, where the Usagaran orogenic belt was thrust onto the craton  
177 and the Ubendian orogenic belt was accreted along the craton's margin because of strike-slip  
178 motion (Daly, 1988; Lenoir et al., 1994). The Ubendian Belt was reactivated several times,  
179 preserving geochronologic, and petrographic and geochemical evidences of successive terrane  
180 accretion (e.g., Lenoir et al., 1994; Boniface and Schenk, 2012; Boniface et al., 2012). Known  
181 terranes within the Ubendian Belt are separated by shear zones which include the Mughese Shear  
182 Zone and the Mtose Shear Zone (Fig. 2; Daly, 1988; Delvaux et al., 2012), where the Chisi Suture  
183 Zone represents the major suture zone between the Precambrian Tanzania Craton and Bangweulu  
184 Block (Boniface and Schenk, 2012). Recent studies have highlighted the role of these shear zones  
185 in fault development (e.g., Morley, 2010; Delvaux et al., 2012; Kolawole et al., 2018) and the

186 distribution of seismicity in southern Tanzania and northern Malawi (Dawson et al. 2017;  
187 Kolawole et al., 2018).

188  
189 *2.2. The Rukwa Rift, Northern Malawi Rift, and the Mbozi Block accommodation zone (RNMRS)*

190 The RNMRS evolved during the Permo-Triassic episode of rifting that affected southern and  
191 eastern Africa, also known as Karoo rifting (Chorowicz, 2005). Outcrops of Karoo sediments have  
192 been mapped along the southern end of the Rukwa Rift (Figure 2) and the northern section of the  
193 North Malawi Rift Basin (Kilembe and Rosendahl, 1992). These sediments lie unconformably  
194 over the Precambrian basement and consist mainly of sandstone, shale, and coal and thicken  
195 towards the border faults providing evidence for reactivation of synthetic faulting in the Permo-  
196 Triassic (Morley, 1992; Delvaux et al., 1992).

197       Cenozoic rifting began in the Upper Miocene, characterized by normal faulting and basin  
198 subsidence with the diagenesis of Red Sandstones and Lake Bed Sediments (Delvaux and Hanon,  
199 1991). Additional subsidence occurred after the deposition of these packages, and in different  
200 directions, evidenced by the drag orientations of sediment packages on the faults (Kilembe and  
201 Rosendahl, 1992). The Cenozoic rifting featured the reactivation of older faults as seen in seismic  
202 profiles of the Rukwa Rift in which the faults are mostly contiguous from Karoo sediments to Red  
203 Sandstones to Lake Beds (Kervyn et al., 2006). The present-day tectonic activity in the RNMRS  
204 consists of limited volcanic eruptions, minor seismicity in the Mbozi Block region, and continued  
205 sedimentation in the Rukwa and North Malawi basins (Delvaux and Hanon, 1991).

206       The present-day architecture of the RNMRS consists of the Rukwa Rift to the northwest  
207 of the segment, with the Lupa Fault (generally considered the border fault) bounding it to the  
208 northeast and the Ufipa Fault to the SW (Fig. 1B). Towards the southeastern end of the Rukwa



209 Rift. It bifurcates around the Mbozi Block forming the Songwe Trough (ST) to the northeast and  
210 the Musangano Trough (MT) to the southwest. The Mbozi Block transitions into the North Malawi  
211 Rift (also known as the North Basin) which represents the southeastern end of the RNMRS and it  
212 consists of a half-graben, bounded to the northeast by the Livingstone Fault (Fig. 1B). The Mbozi  
213 Block is referred to as an accommodation zone because it is thought to accommodate and transfer  
214 relative strain between the Rukwa and North Malawi Rift Basins (Delvaux and Hanon, 1993)

215         The Mbozi is a mass of Precambrian basement that is composed of Meta-basites and  
216 intermediate granulites and quartzites of the Mbozi Terrane (Daly, 1988) and is bounded to the  
217 southwestern by the Mughese Shear Zone (Fig. 2B), and overlain on the northeast by the volcanic  
218 deposits of the Rungwe Volcanic Province (RVP). The RVP is a ~1500 km<sup>2</sup> area of volcanic rocks  
219 and structures that evolved ca. 9 Ma (e.g., Fontijn et al., 2012), and a strong tectonic control on  
220 the localization of volcanic centers have been inferred (e.g., Fontijn et al., 2010, 2012). To the  
221 northeast of the RVP, a poorly defined NE-trending rift basin occurs, known as the “Usangu  
222 Basin”, where Permo-Triassic to Recent sedimentary rocks overlie the Precambrian basement  
223 (Mbede, 2002).

224         The crustal thickness beneath the Rukwa Rift is ~37.5 km (Kim et al., 2009), but varies  
225 between ~33 km and ~39 km along the rift shoulder (Ufipa Plateau) (Hodgson et al., 2017), and  
226 increases slightly to 41.1–42.1 km in the northwestern-most part of the rift where the rifting is  
227 minimal. These suggest that overall, the crustal thinning beneath the rift has been minimal but may  
228 be slightly more beneath the Songwe Trough (Njinju et al., 2018). Camelbeeck and Iranga (1996)  
229 estimated ~42 km crustal thickness beneath the Songwe Trough. Whereas, an average crustal  
230 thickness of 39 km has been estimated for the Rungwe Volcanic Province, ~37-39 km for the North

231 Malawi Rift, and 38-42 km for the Proterozoic terrains surrounding the North Malawi Rift  
232 (Borrego et al., 2016; Njinju et al., 2018).

233

### 234 *2.3. Kinematics of the RNMRS*

235 The mode of opening of the Rukwa Rift – Northern Malawi Rift segment is controversial. Overall,  
236 two models have been proposed. One of the models advocates for orthogonal rifting due to the  
237 dominance of NW-trending pre-existing basement fabric in the region, which resulted in the  
238 rotation of the E-W directed regional extension into NE-SW, thus producing NW-striking normal  
239 faults (e.g., Delvaux et al., 1992; Morley, 2010; Delvaux et al., 2012). The other model argues for  
240 oblique extension primarily due to the obliqueness of the rift segment to the E-W directed  
241 extension, thus resulting in the development of NW-trending dextral strike-slip faults (e.g.,  
242 Chorowicz, 1989; Daly et al., 1989; Wheeler and Karson, 1994; Kervyn et al., 2006; Mortimer et  
243 al., 2007). Both models are based on observations from only the Rukwa Rift and North Malawi  
244 Rifts, and did not consider the kinematics of brittle structures along the Mbozi Block  
245 accommodation zone.

246

## 247 **3.0 MATERIAL AND METHODS**

248 In this study, we carried out detailed mapping of exposed and buried fault segments within the  
249 RNMRS. We utilized Shuttle Radar Topography Mission (SRTM) Digital Elevation Model  
250 (DEM) to locate surface expressions of faults; and filtered aeromagnetic data to map the plan-view  
251 trace of basement faults and metamorphic fabrics.

252

### 253 *3.1. SRTM DEM Data*

254 We extracted topographical profiles along the length of the rift from the SRTM DEM data to  
255 investigate surface morphology of the rift segments which could provide insight into the evolving  
256 nature of the rift architecture along the RNMRS.

257

### 258 *3.2. Aeromagnetic Data*

259 We combined three separate aeromagnetic surveys consisting of data acquired over northeastern  
260 Zambia, southern Tanzania and Northern Malawi. The Tanzania survey was collected between  
261 1977-1980 with flight height of 200 m and a flight line spacing of 1 km. The Zambia survey was  
262 collected between 1973-1976 with a flight height of 150 m and a flight line spacing of 800-1000  
263 m. The Malawi survey was carried out in 2013 with a flight height of 80 m, a flight line spacing  
264 of 250 m. Before merging the three surveys, we first corrected for the skewness of the data by  
265 reducing each of them to the magnetic pole (RTP). The RTP correction normalizes the magnetic  
266 field to the magnetic field at the pole so the anomalies retain their correct strike and shape, allowing  
267 the magnetic data to be interpreted as geologic structures (Baranov, 1957; Silva, 1986).  
268 Afterwards, we applied upward-continuation (Henderson and Zeitz, 1949) of 120 m to the RTP-  
269 corrected Malawi data, 50 m to the Zambia data in order to mathematically normalize the three  
270 datasets to a 200 m observational height. We then merged the three surveys into a single  
271 aeromagnetic grid file. Further, we applied the vertical derivative (VDR) filter to the merged data  
272 in order to enhance magnetic gradients associated with possible basement faults and basement  
273 metamorphic fabrics (Salem et al., 2008).

274 The vertical derivative edge filter has been very effective in the mapping of plan-view trace  
275 of buried active faults from aeromagnetic data in different parts of the EARS (Kinabo et al., 2007,  
276 2008; Kolawole et al., 2017, 2018). Excluding the Rungwe Volcanic Province (RVP; Figure 3)

277 where volcanic materials overlie the crystalline basement, there is no information on the presence  
278 of basaltic rocks along the fault segments interpreted in this study. Therefore, we assume induced  
279 magnetization as the primary source of magnetization, except in the Rungwe Volcanic Province  
280 (RVP) where volcanic deposits are present. However, we do not have information on remanent  
281 magnetization in the RVP at this time. Due to the higher spatial resolution of the Malawi  
282 aeromagnetic data (62 m grid cell size) compared to those covering Zambia (225 m grid cell size)  
283 and Tanzania (250 m grid cell size), the magnetic anomalies are most significantly better resolved  
284 in the Malawi part of the filtered aeromagnetic maps.

285

## 286 **4.0 RESULTS**

### 287 *4.1. Variation in rift morphology from topographic profiles*

288 We examined fifteen rift-orthogonal topographic profiles (spaced at 40 km) along the RNMRS  
289 (Fig. 1B) to understand the overall along-strike variation in rift morphology. The investigation of  
290 rift dynamics by careful analyses of the topographic structures has provided important information  
291 on the subsurface architecture of rift systems (e.g., Pik et al., 2008; Wichura et al., 2011; Lao-  
292 Davila et al., 2015). Our morphological assessments focus on the variation in the scarp-heights  
293 (relief above the surface) of exposed normal faults along the RMNRS. This provides the minimum  
294 estimate of the relative vertical displacements of the faults at the point of assessment, hence the  
295 term ‘exposed minimum vertical displacement’ (EMVD) (Lao-Davila et al., 2015).

296 Profile 1 (Fig. 3), obtained at the northern tip of the Rukwa Rift shows no pronounced fault  
297 scarps, and the slight topographic high between Lake Tanganyika and Ufipa Fault represents the  
298 northernmost tip of the Ufipa Plateau. In Profile 2, the surface morphology of the rift shows sharp  
299 topographic gradients bounding the Rukwa Rift Valley. These topographic gradients correspond

300 to the scarps of the Ufipa Fault (600 m) and the Lupa Fault (750 m). In this northern part of the  
301 Rukwa Rift, the Ufipa and Lupa Faults have comparable scarp heights, thus illustrating a typical  
302 graben structure. In Profile 3, the rift structure changes into a half-graben surface morphology with  
303 the Ufipa Fault having a significantly higher escarpment than the Lupa Fault (~900 m difference).  
304 Profiles 4 to 7 show the same half-graben morphology for the Rukwa Rift as in Profile 3; however,  
305 we observe that the Ufipa Fault scarp is much higher than the topography of the Ufipa Plateau to  
306 its west along Profile 4.

307         Along Profiles 6 and 7, we observe that the Ufipa Fault scarp is lower than in the northern  
308 profiles (Profiles 1-5) and that the Lupa Fault scarp is also higher than in the northern profiles. In  
309 Profile 7, the Rukwa Rift splits into two basins separated by the Mbozi Block such that the west  
310 basin (Musangano Trough) is bound by the Ufipa Fault to the southwest, and the east basin  
311 (Songwe Trough) is bound by the Lupa Fault to the northeast. Profiles 7 to 9 shows a continuous  
312 southeastward decrease in the scarp heights of the Ufipa and Lupa Faults; and although the Ufipa  
313 Fault scarp is still visible south of the Mbozi Block along Profile 9, the Lupa Fault scarp is  
314 significantly diminished. Profile 9 shows a gentle topographic transition from the Musangano  
315 Trough to the Mbozi Block, but to the northeast of the Mbozi Block, the topography spikes  
316 abruptly, representing the northern limits of the Rungwe Volcanic Province (RVP). In Profile 10,  
317 the Ufipa Fault bounds what appears to be the southernmost extent of the Musangano Trough,  
318 while the uplifted Mbozi – RVP domain dominates the terrain and drops off into the Usangu  
319 Trough to the northeast. Profile 11 transects the northernmost tip of the North Malawi Rift, where  
320 the RVP (bounded to the northeast by the Livingstone Fault scarp) represents the most dominant  
321 structure in the terrain and the entire topography of the Mbozi Block and areas to its southwest are  
322 relatively lower.

323 Profiles 12 and 13 illustrate half-graben morphologies for the North Malawi Rift (North  
324 Basin) with the Livingstone Fault (northeast bounding fault) dominating the topography. Profile  
325 14 transects the transfer zone between the North and Usisya Basins of the Malawi Rift showing  
326 both the Livingstone border fault to the northeast and the Nyika Plateau to the southwest. Profile  
327 15 which transects the Usisya Basin describes a half-graben surface morphology but in which the  
328 rift bounding fault is located on the southwest.

329

#### 330 *4.2. Aeromagnetic lineaments and basement fabric*

331 The RTP merged (Fig. 4A) and edge-enhanced (Fig. 4B) aeromagnetic maps over the RNMRS  
332 provide a continuous plan-view image of the basement structures along the rift segment. Although  
333 the Malawi part of the merged data has the highest resolution, the moderate resolution of the  
334 Tanzania and Zambia parts of the data allows for considerable delineation of the trends of magnetic  
335 anomalies. Overall, the areas of basement exposures exhibit high amplitude, high frequency and  
336 short wavelength magnetic anomalies that delineate lineaments of interpretable trends (e.g.,  
337 Kolawole et al., 2018). The high frequency lineaments can be easily observed on the rift shoulders  
338 of the Rukwa and North Malawi Rifts (Fig. 4B), and are commonly truncated at the rift margins  
339 by the rift-bounding faults (black arrows in Fig. 4B).

340 Within the rift valleys where sedimentary rocks overlie the deeply-buried basement rocks,  
341 the detailed magnetic fabric of the basement becomes suppressed such that gradients in the  
342 magnetic data could correspond to fault offset within the magnetic source (e.g., Grauch and  
343 Hudson, 2007, 2011; Kolawole et al., 2018) or remnants of the suppressed magnetic foliation of  
344 the source (Kolawole et al., 2018). In the study area, the magnetic anomalies within the rift basins  
345 are dominated by relatively lower amplitude, longer wavelength and lower frequency anomalies.

346

### 347 *4.3. SRTM DEM Fault trends and Aeromagnetic lineaments*

348 We compare the along-axis geometry of the rift-bounding faults (from SRTM DEM) with the  
349 metamorphic fabric (in plan view) of the host basement rocks along the rift shoulders (from filtered  
350 aeromagnetic data) (Figs. 5-11). Figures 5-9 focus on the southwestern boundary of the RNMRS,  
351 consisting of the Ufipa Fault of the Rukwa Rift, the southwestern boundary of the Mbozi Block  
352 and the southwestern boundary faults of the North Malawi Rift. Whereas, Figures 10 and 11 focus  
353 on the northeastern boundary of the RNMRS, consisting of the Lupa Fault of Rukwa Rift, the  
354 northeastern boundary of the Mbozi Block (i.e. the Rungwe Volcanic Province) and the  
355 Livingstone Fault of the North Malawi Rift. We constrain our identification of the Precambrian  
356 terranes and strike of their fabrics with previous field studies of the Precambrian basement along  
357 the RNMRS (e.g., Daly, 1988; Wheeler and Karson, 1989; Lenoir et al., 1994; Theunissen et al.,  
358 1996; Boven et al., 1999; Fernandez-Alonso et al., 2001; Ring et al., 2002; Boniface and Schenk,  
359 2012; Delvaux et al., 2012, Lawley et al., 2013; Kolawole et al., 2018). Overall, within the study  
360 area, we observe that the basement fabrics exhibit two styles, (1) discrete fabrics which include  
361 isolated magnetic lineaments of strong amplitude; and (2) distributed fabrics which encompass  
362 fabric sets of multiple medium-to-low amplitude magnetic lineaments as distributed fabrics.

363

#### 364 *4.3.1. Southwestern boundary of the RNMRS*

365 In the northernmost part of SW Rukwa Rift (Chisi area) (Figs. 5A-C), we observe curvilinear fault  
366 geometries that follow Precambrian fabric (e.g., Ufipa, Chisi, Kalambo and Kanda Faults). In the  
367 Chisi area, the Rukwa Rift border fault consists of the Northern Ufipa Fault segment and the Chisi  
368 Fault segment. The tip of the Northern Ufipa Fault segment terminates against the WNW-ESE

369 Chisi Fault at a high angle (Fig. 5A). The Chisi Fault aligns with a strong WNW-ESE magnetic-  
370 high lineament (discrete fabric) (Fig. 5B-C) consistent with the Chisi Suture Zone, which extends  
371 eastward into the rift basin (Theunissen et al., 1996; Boven et al., 1999; Boniface and Schenk,  
372 2012; Fig. 2B). Also, the truncated Ufipa Fault segment aligns with the Ufipa Terrane basement  
373 fabrics (distributed fabrics). The North Ufipa Fault and Chisi Fault link at a very high angle to  
374 form a salient that point basinward (the Chisi Salient).

375 In the central part of the Ufipa Fault (Figs. 6A-C), the fault segments also exhibit  
376 curvilinear geometries and the hard linkage of major fault segments occur at high angles  
377 (e.g., Kwera relay ramp). The Kwera relay ramp is the largest relay zone along the Ufipa Fault. To  
378 the north of the Kwera relay ramp, the fault trends parallel to a magnetic lineament (discrete fabric)  
379 that is located to its east, whereas, to the west of this fault segment, the basement is characterized  
380 by two cross-cutting sets (NNW-SSE and NW-SE) of distributed fabrics. The NNW-SSE set  
381 represent the fabrics of the Ufipa Terrane, but the origin NW-SE is unknown at this time. The  
382 Ufipa Fault segments appear to follow the NNW-SSE basement fabrics but side-steps by means  
383 of short fault segments that align with the NW-SE fabric set. To the south of the relay ramp,  
384 the Ufipa Fault strikes parallel to the Mughese Shear Zone fabric which is colinear with the NNW-  
385 SSE set.

386 Towards the southern part of the Ufipa Fault, in Figures 7A-C, we observe that  
387 the Ufipa Fault segments exhibit rectilinear geometries such that it is difficult to delineate fault  
388 bends that could correspond to breached relay ramps. In addition, we observe a stronger alignment  
389 of the Ufipa Fault segments with the Mughese Shear Zone fabric within the area. To the east of  
390 the Ufipa Fault, a fault that strikes parallel to the Ufipa Fault separates the Musangano Trough  
391 from the Mbozi Block. The Mbozi basement is characterized by metamorphic fabrics that strike



392 WNW-ESE to NW-SE, oblique to the fault but in which subtle bends in the fault trend align with  
393 the basement fabric.

394 In the southern part of the Ufipa Fault (Figs. 8A-C), the fault is characterized by two  
395 segments. One of the segments represents a rectilinear southward continuation of the Ufipa Fault  
396 and is bounded to the east by a linear ridge that separates it from the Musangano Trough (see  
397 “Mughese Fault” segment at Tunduma in Figs. 8A-C). The other segment splays away from the  
398 former and delineates a curvilinear geometry that looks like those in the northern and central  
399 segments of the Ufipa Fault; this curvilinear segment bounds the southernmost part of  
400 the Musangano Trough (see “Ufipa Fault” in Figs. 8A-C). Around Kaseye town (see Fig. 8A), the  
401 basement is partially buried and more deeply buried around Chitipa to the south. The continuation  
402 of the Ufipa Fault is only evident in the aeromagnetic data as a strong magnetic-low lineament that  
403 is bounded by bands of magnetic-high lineaments (see magnetic fabrics around Kaseye town in  
404 Fig. 8B). Within the Kaseye area, the NW-striking Mughese Shear Zone fabrics are truncated by  
405 a discrete N-S trending magnetic-high lineament (see area within purple rectangle in Fig 8C). The  
406 magnetic-low lineament that projects as a southward continuation of the Ufipa Fault persists along  
407 the Mughese Shear Zone fabric into the Karonga area of the North Basin of Malawi Rift where  
408 the Mughese Shear Zone is abruptly truncated by the Karonga Fault (KF in Fig. 8C). The Mbozi  
409 Terrane fabric strike NW-SE, at low angles to the trend of the Mughese Shear Zone.

410 Detailed analyses of the onshore faults along the hinge zone of the Northern Malawi Rift  
411 (Karonga area) are well documented in Kolawole et al. (2018). Major onshore hinge zone faults  
412 include the Karonga Fault (KF), St. Mary Fault (SMF), Kaporo Fault (KPF), Lupaso Fault (LF),  
413 Katesula Fault (KTF) and the Mbiri Fault (Figs. 9A-C). Although the Karonga Fault cuts the  
414 basement fabric, several basement-rooted buried fault segments along the rift margin align with

415 the fabric of the Mughese Shear Zone (Kolawole et al., 2018). It is interesting to note that  
416 the Mbiri Fault, the longest fault (and potentially has the largest throw?) along the rift margin is  
417 sub-parallel to the strike of the continuation of the Ufipa Fault into the area (“Mughese Fault” in  
418 Fig. 9C). Although segments of the Mbiri Fault appear to align with the Mughese Shear  
419 Zone fabric, it is not clear if the fault reactivated the southwestern boundary of the shear zone or if  
420 the fault partially aligns with the fabric of the shear zone. However, we observe that for the most  
421 part, the side-steps along the Mbiri Fault align with the basement fabric.

422

#### 423 *4.3.2. Northeastern boundary of the RNMRS*

424 In the northern part of the Lupa Fault, the fault trend defines long, rectilinear segments (Fig. 10A)  
425 and aligns with the Katuma Terrane, similar to those observed in the southern part of  
426 the Ufipa Fault where faults align with the trend of the Ufipa Terrane (Fig. 7). Although, the E-W  
427 trending fabric of the Usagaran Orogenic Belt dominates the aeromagnetic data along the  
428 northeastern Rukwa Rift shoulder (Fig. 10B), we also observe that closer to the Lupa Fault scarp,  
429 there are some lineaments that align with the fault. To the southwest of the Lupa Fault (within the  
430 rift valley), a strong magnetic-high lineament which correspond to the Chisi Suture Zone (see  
431 onshore continuation and outcrop of the shear zone in Fig. 5), strike sub-parallel to the trend of the  
432 Lupa Fault, but deviates more significantly southwards (Figs. 4B and 10).

433 The southern part of the Lupa Fault (between the Katuma Terrane and the Rungwe  
434 Volcanic Province) is characterized by curvilinear fault segments (Fig. 10 and 11). The Lupa  
435 Terrane fabrics are oriented WNW-ESE, oblique to the Lupa Fault trend (Figs. 11A-C). However,  
436 subtle steps along the curvilinear fault segments align with the Lupa Terrane fabrics.

437 In the Rungwe Volcanic Province (RVP), the magnetic lineaments strike NW-SE (Fig.  
438 11B), similar to those of the Mbozi Terrane (8B and C), and are truncated to the west by a strong  
439 NNW-striking magnetic high lineament (white arrows in Fig. 11B). Furthermore, we observe that  
440 the volcanic centers align with NNW-striking magnetic gradient superimposed on the NW-striking  
441 fabrics (black arrows in Fig. 11B). South of the Rungwe Volcanic Province, segments of the  
442 Livingstone Fault system describe rectilinear geometries and align with strong magnetic-high  
443 lineaments (shear zone?) in the Upangwa Terrane.

444

## 445 **5.0 DISCUSSION**

### 446 *5.1. Rift architecture*

447 The present morphology of the RNMRS reflects the result of multiple episodes of rifting that have  
448 affected this part of eastern Africa i.e. a Permo-Triassic rifting episode (Karoo), a Cretaceous  
449 episode and the ongoing Cenozoic rifting episode (e.g., Castaing, 1991; Morley et al., 1992). The  
450 Rukwa Rift has been described as both a graben (e.g., Zhao et al., 1997) and half-graben (e.g.,  
451 Kilembe and Rosendahl, 1992) bounded by the oppositely-dipping Ufipa and Lupa normal faults.  
452 The Lupa Fault is commonly regarded as the major border fault of the Rukwa Rift due to its larger  
453 throw of ~7 km (Peirce and Lipkov, 1988) relative to the Ufipa Fault (Fig. 12); however, it has  
454 also been shown that the Cretaceous and Cenozoic sediments in the rift thicken towards both faults  
455 (Fig. 12; Morley et al., 1992; Zhao et al., 1997). In this study, our topographical assessments (Fig.  
456 3, profiles 1-7) show that the scarp height of the Ufipa Fault consistently exceeds that of the Lupa  
457 Fault through-out the rift segment, thus suggesting significant footwall uplift along the Ufipa Fault.

458 The significantly lower scarp-height of the Lupa Fault suggests either that it has not been  
459 very active in Cenozoic times or that it has been heavily eroded since the cessation of Mesozoic

460 rifting. However, based on these observations, we interpret that in the earlier rifting episodes  
461 (especially in the Permo-Triassic Karoo episode), the Lupa Fault played the role of the major  
462 border fault such that the basin defines a typical half-graben geometry; but in the present Cenozoic  
463 phase of rifting, the Ufipa Fault appear to have been preferentially accommodating more strain.  
464 Therefore, we suggest that the Rukwa Rift is possibly transitioning into an asymmetric-graben  
465 geometry. An asymmetric-graben is a graben with EMVD greater on one border fault compared  
466 to the other one, such that the basin polarity has shifted to the fault with the greater 'exposed  
467 minimum vertical displacement' (EMVD) (Lao-Davila et al., 2015). The implications of the  
468 present Rukwa Rift morphology on the Lupa Fault may reflect temporal and spatial migration of  
469 strain accommodation from a previously dominant border fault into another one that has been  
470 previously less-dominant. This could possibly be explained by the Scholz and Contreras (1998)  
471 suggestion that when a rift-bounding fault attains some limiting offset, motion on the fault will  
472 cease, and strain will be transferred to a new fault.

473

## 474 *5.2. The Southwestern Boundary of the RNMRS and relationships with Precambrian Basement* 475 *Fabric*

476 In the Chisi area, the Northern Ufipa Fault segment terminates against the Chisi Suture Zone along  
477 which the Chisi Fault segment developed. The termination of the Ufipa Fault at its intersection  
478 with this shear zone exemplifies one of the roles of pre-existing basement structures as temporal  
479 and/or spatial mechanical 'barriers' that arrest and delimit the continuous lateral propagation of a  
480 fault. Several studies on fracture propagation have demonstrated that fractures are principally  
481 bifurcated, blunted, and/or arrested when they intersect discontinuities, stress barriers and/or rock  
482 layers of significantly-contrasting mechanical properties along their path of propagation (e.g.,

483 Helgeson and Aydin, 1991; Gudmundsson and Brenner, 2001; Zhang et al., 2007; Zhang and  
484 Jeffrey, 2008). Other examples of normal fault termination at long-lived basement shear zones  
485 include the case of the Albertine-Rhino Graben terminating at the Aswa Shear Zone (Katumwehe  
486 et al., 2015) and the Okavango Rift border faults against the Sekaka Shear Zone (Modisi et al.,  
487 2000). We suggest that both the reactivation of the Chisi Suture Zone into the Chisi Fault and  
488 termination of fault segments at the shear zone demonstrate the strong influence of the Chisi Suture  
489 Zone on the development of this part of the Rukwa Rift.

490         Although the northern segments of the Ufipa Fault align with the basement fabrics (Fig.  
491 5B-C) and the southern segments show even stronger alignment with the NNW-SSE fabrics of the  
492 Ufipa Terrane and/or Mughese Shear Zone (Fig. 7), we find that the central segments of the fault  
493 show only partial alignment with this basement fabric (Fig. 6A-C). These observations imply that,  
494 although the Ufipa Fault is thought to have largely propagated along the Mughese Shear Zone  
495 (Fig. 2; Delvaux et al., 2012), there is stronger control of the Mughese Shear Zone and Ufipa  
496 Terrane fabrics on the fault development along its northern and southern segments than in the  
497 central part. We suggest that the partial control of these NNW-SSE fabrics on the central Ufipa  
498 Fault segments is due to the occurrence of a NW-SE basement fabric set on the Mughese Shear  
499 Zone and Ufipa Terrane fabric (Fig. 6). This may also explain the localization of the largest relay  
500 zone along the Ufipa Fault at its central segment.

501         The Tunduma-Kaseye area of Malawi, through the Misuku Mountains (Fig. 8A) constitute  
502 the southern boundary of the Mbozi Block. Although, the SRTM DEM shows that the sub-aerial  
503 expression of the Ufipa Fault dies out roughly mid-way between Tunduma and Kaseye, the filtered  
504 aeromagnetic data reveals that in the subsurface, the fault continues across the Kaseye-Chitipa area  
505 as a distinct magnetic-low lineament that bounds the Mughese Shear Zone to the south and runs

506 southeastwards into the Karonga area (Fig. 8B). Upon closer observation of the continuation of  
507 this strong magnetic-low lineament in the Kaseye-Chitipa area, we find that it cuts-across and  
508 offsets a N-S striking magnetic-high lineament which extends 80 km southwards into the Permo-  
509 Triassic Luangwa Rift in Zambia. We interpret this N-S lineament as a mafic dike that is possibly  
510 related to one of the earlier (Triassic or Cretaceous) episodes of rifting which are known to have  
511 been associated with extensive late-stage diking events in the Luangwa Rift (e.g., Van de Velde  
512 and De Waele, 1998) and Shire Graben in southern Malawi (Castaing, 1991). Sedimentary deposits  
513 in the Kaseye-Chitipa area resulted in the burial and lack of sub-aerial exposure of this structure,  
514 thus making this study the first revelation of its existence in Northwestern Malawi.

515         Our analyses of the geometry of the interpreted dike structure (Fig. 13A), here in referred  
516 to as the Chitipa Dike, shows a distinct difference in the geometry of the structure to the north  
517 where it is cut by the strong magnetic-low lineament (continuation of the Ufipa Fault) and to the  
518 south (farther away from the fault intersection). South of Chitipa (Fig. 13B), we observe that the  
519 north-trending dike describes a consistent left-stepping geometry which diminishes across the  
520 Chitipa town location and continues with a more rectilinear geometry northwards into the Mughese  
521 Shear Zone area. This side-stepping geometry is typical of vertical sheet intrusions and are related  
522 to either magma intrusion into pre-existing stepped joint systems (e.g., Baer, 1991) or near-surface  
523 stress rotations during magma intrusion (e.g., Fossen, 2010). In this study, the coincidence and  
524 strike of the dike-steps along the NW- to NNW- striking basement fabric may in fact suggest the  
525 possible influence of pre-existing basement fabric on the stepping geometries of dike intrusions  
526 during their emplacement in host metamorphic rocks (Fig. 13B).

527         Further north, where the dike is cut by the continuation of the Ufipa Fault, the filtered  
528 aeromagnetic data shows the dike exhibiting consistent right-lateral offsets across NW-SE

529 magnetic gradients (Fig. 13C). This clear distinction in the structural style of the dike south of  
530 Chitipa and in the north across the continuation of the Ufipa Fault, suggest that the contrasting  
531 structural styles are associated with different geological processes. In a summary, we interpret that  
532 along the southern boundary of the Mbozi Block, the continuation of the Ufipa Fault, which itself  
533 aligns with the Mughese Shear Zone fabric (Fig. 8B-C), is a right-lateral strike-slip fault that  
534 displaced a N-S trending Mesozoic (?) dike intrusion (Fig. 13C). We further interpret that this  
535 strike-slip fault reactivated the Precambrian Mughese Shear Zone at some time post-Cretaceous  
536 (i.e. related to the present Cenozoic rifting phase), and therefore refer to it as the “Mughese Fault”.  
537 This interpretation is further supported by the change in the morphological expression of the Ufipa  
538 Fault from a typical single-scarp style into a narrow linear valley-ridge style in the Tunduma area  
539 in the SRTM DEM (see “linear ridge” in Fig. 8A). The observed linear valley-ridge  
540 geomorphology is typical of active strike-slip fault zones (e.g., McCalpin et al., 2009). In addition,  
541 previous field studies in the area (Delvaux et al., 2012) observed strike-slip displacement on rock  
542 outcrops at Tunduma and Mbozi Quarry (“Q” in Fig. 8A). Using the Chitipa Dike as a strain  
543 marker, we observe that the offsets increase northwards across multiple splays of the Mughese  
544 Fault and estimate that the displacement is maximum at the major Mughese Fault trace  
545 (northernmost extent of the strike-slip fault zone). Since mafic intrusions often produce magnetic  
546 anomalies larger than the actual size of the sources, it is practically impossible to estimate the true  
547 cumulative strike-slip displacement from the aeromagnetic data. Based on the lateral dike  
548 separation across the fault on our aeromagnetic data, we estimate a minimum of 500 m lateral  
549 displacement along the Mughese Fault (Fig. 13C). It is also possible that this estimated offset only  
550 represents the lateral component of an oblique-normal slip along the fault. In Figure 14, we present

551 a conceptual model that summarizes our interpretation of the Chitipa Dike geometry and the  
552 interaction of the Mughese Fault with the dike.

553         However, in Tunduma area (Fig. 8A), the presence of discrete breaching of the linear ridge  
554 by stream channels suggest that the strike-slip displacement along the Mughese Fault is most-  
555 likely a short-lived event that occurred at some time in the past during the development of the  
556 RNMRS. The curvilinear fault scarp adjacent to the Mughese Fault at Tunduma shows single-  
557 scarp morphology (not linear-ridge morphology) typical of normal faults as seen on the other  
558 segments of the Ufipa Fault. Therefore, we interpret this curvilinear fault scarp as a possible old  
559 segment of the Ufipa Fault that was ‘pirated’ by the Mughese strike-slip fault; thus, suggesting a  
560 phase in which the Ufipa Fault accommodated strike-slip displacement.

561         Along the southwest margin of the North Malawi Rift (Karonga area), the Mughese Fault  
562 diffuses into a zone of wide-spread faulting where the southeast-ward bend of the Mughese Shear  
563 Zone controls the development of the normal faults and recent seismicity along the basin hinge  
564 margin (Fig. 9A-C) (Kolawole et al., 2018; Dawson et al., 2018). Further south of Karonga town,  
565 the NNW-striking Mbiri Fault is the dominant fault structure in terms of its length (and  
566 displacement?) along this part of the hinge zone of the North Malawi Rift. We do not observe any  
567 direct spatial connectivity between the Mughese Fault and the Mbiri Fault. However, based on the  
568 sub-parallel geometry of both faults and the structural dominance of the Mbiri Fault in the area,  
569 we suggest that the Mbiri Fault could possibly represent a continuation of the Mughese Fault into  
570 the hinge zone of the Malawi Rift North Basin. It is also important to note that the Mbiri Fault is  
571 synthetic to the Livingstone border Fault. Following the observations and interpretations above,  
572 we suggest that there exists a well-developed continuous connectivity of rift-related structures  
573 along the southwestern boundary of the RNMRS, facilitated by the extent of the Mughese Shear



574 Zone and the Ufipa Terrane. Interestingly, the linking of the oppositely-dipping Ufipa and Mbiri  
575 Faults by the Mughese strike-slip fault describes a structure that, overall, is similar to that of the  
576 Morley et al. (1990) convergent-approaching normal fault system.

577

### 578 *5.3. The Northeastern Boundary of the RNMRS and relationships with Precambrian Basement* 579 *Fabric*

580 The northern segment of the Lupa Fault exhibits clear alignment with the trend of the Katuma  
581 Terrane (Fig. 10) and with a few interpretable magnetic lineaments (likely due to low resolution  
582 of the aeromagnetic data). We also note that the Lupa Fault is sub-parallel to the Chisi Suture Zone  
583 in this area. Farther south of the Lupa Fault (Kapalala-Kanga area; Figs. 10 A-C), the fault  
584 segments occur at a high angle to the Usagaran Belt and Lupa Terrane fabrics, thus indicating an  
585 apparent lack of control of pre-existing basement fabric on the propagation of the southern Lupa  
586 Fault, except in the coincidence of the fault steps with the trend of the basement fabrics.

587         The southern segment of the Lupa Fault transitions into the Rungwe Volcanic Province  
588 (RVP) where surficial cover of volcanic deposits obscures the southward continuation of the Lupa  
589 Fault (Fig. 11A). In addition, the presence of mafic volcanic deposits in the RVP (e.g., Fontijn et  
590 al., 2012) makes it difficult to make a reliable interpretation of the magnetic fabric of the  
591 underlying Precambrian basement (Fig. 11B). However, we find that a distinct magnetic-high  
592 lineament aligns with the Mbaka Fault surface trace (white arrows in Figs. 11A and 11B). Also,  
593 the distribution of volcanic centers in the RVP show alignment with both the Mbaka Fault trace  
594 and a subtle curvilinear gradient (black arrows in Fig. 11B). Further south, the curvilinear gradient  
595 connects with the Livingstone Fault, the northeastern border fault of the North Malawi Rift. This  
596 curvilinear gradient coincides with the location and extents of the so-called “Ngozi-Rungwe Line”

597 of Fontijn et al. (2010), described as a buried fault system that served as a conduit for magmatic  
598 fluids to migrate to the surface volcanic vents. Therefore, although it is possible that the magnetic  
599 anomalies in this area are affected by remanent magnetization from the volcanic deposits, we  
600 interpret that this aeromagnetic gradient provides a possible subsurface evidence of the fault  
601 system (Ngozi-Rungwe Line) that connects the Lupa Fault and the Livingstone Fault across the  
602 RVP. The filtered aeromagnetic data and previous field studies (e.g., Wheeler and Karson, 1989)  
603 shows that the Livingstone Fault segments align with and reactivated the fabric of the Upangwa  
604 Terrane (Figs. 11B-C). The observations and interpretations above suggest that there exists a well-  
605 developed continuous connectivity of rift-related structures along the northeastern boundary of the  
606 RNMRS. However, the relationship between the basement fabric and the buried faults beneath the  
607 volcanic deposits remains unclear.

608

#### 609 *5.4. Implications for Rift Development*

##### 610 *5.4.1. Rift Coupling*

611 In the Rukwa Rift, the substantial dominance of the Ufipa Fault rift shoulder over that of the Lupa  
612 Fault may imply that the Ufipa Fault is the present-day active border fault of the Rukwa Rift. This  
613 proposition may be supported by the hypocentral location of the 1994 Mw5.9 Rukwa earthquake  
614 and its aftershocks with epicentral location in the northern part of the rift (Fig. 12; Zhao et al., 1997).  
615 The nodal planes of the earthquake focal mechanism solution are broadly consistent with the  
616 orientation of both the Lupa and Ufipa faults, and relative position of aftershocks to the main shock  
617 is well determined (Fig. 12; Zhao et al., 1997). Considering the uncertainty range of the  
618 earthquakes, the spatial distribution of the aftershocks relative to the main shock delineates a sub-  
619 horizontal fault zone that most fits the subsurface projection of the Ufipa Fault (Fig. 12). In

620 addition, field investigations of the Kwera relay ramp (see Fig. 6 for location) revealed features  
621 that indicate recent activity along the Ufipa Fault (Delvaux et al., 2012). Camelbeeck and Iranga  
622 (1996) observed several lower crustal seismicity in the Rukwa Rift with most of the events  
623 clustering beneath the Songwe Trough and the Rungwe Volcanic Province (southern parts of the  
624 rift; Fig. 1B). The locations of the clusters suggest activity along the southern Lupa Fault and  
625 Mbeya Range Fault. However, since the scarp height (and throw?) of the Ufipa Fault decreases  
626 southwards (Fig. 3), and the throw on the Lupa Fault increases southwards (and rapidly along the  
627 Songwe Trough) (Morley et al., 1992), we infer that the present border fault role of the Ufipa Fault  
628 excludes the southermost parts of the Rukwa Rift.

629         It has also been observed that the early stage of continental rifting is typically characterized  
630 by the development of along-axis alternating polarity of rift segments, rift border faults, uplifted  
631 rift flanks (e.g., Bosworth, 1985; Rosendahl, 1987; Hayward and Ebinger, 1996; Lao-Davila et al.,  
632 2015). The zones of polarity changes (transfer/accommodation zones) serve to transfer extensional  
633 strain between the rift segments and link the border faults which often have variable structural  
634 styles and geometries (e.g., Morley et al., 1990; Wilson, 1999). Within young continental rift  
635 settings, interactions between these large border faults lead to the systematic coupling of border  
636 faults and rift segments across the transfer zones, and subsequent growth of the rift system (e.g.,  
637 Corti, 2012). Along the RNMRS, the alternating location of the of rift shoulder uplift (SW in  
638 Rukwa Rift and NE in North Malawi Rift), typical of coupled rift segments, suggest that the  
639 RNMRS can be considered a coupled rift segment. Further, our study here shows that there is in  
640 fact, continuous structural continuation along the northeastern and southwestern margins of the  
641 RNMRS, typical of a coupled rift segment. Although, studies in the EARS and illustrations of its  
642 rift segments had always assumed this to be true, we hereby provide evidence supporting it, for

643 the first time. In the West Antarctic rift system, the localization of recent volcanism along  
644 transverse structures within an accommodation zone (the Discovery accommodation zone)  
645 suggests active structural interactions between the flanking rift segments (Wilson, 1999).  
646 Therefore, we further suggest that the focusing of Neogene volcanism (e.g., Fontijn et al., 2010,  
647 2012) along the northeastern boundary faults of the Mbozi accommodation zone (Fig. 15A) may  
648 be indicative of the ongoing coupling of the Rukwa and North Malawi Rift's northeastern border  
649 faults.

650

#### 651 *5.4.2. Rift Kinematics*

652 Several studies have suggested that the development of the RNMRS has been dominated by dextral  
653 strike-slip kinematics (e.g., Chorowicz, 1989; Daly et al., 1989; Wheeler and Karson, 1994;  
654 Kervyn et al., 2006; Mortimer et al., 2007). However, analyses of fault architecture, fault-  
655 kinematics, paleostress and present-day earthquake focal mechanism solution in the Rukwa Rift  
656 show that the present-architecture of the rift largely developed within a pure extensional setting  
657 with extension direction orthogonal to the trend of the RNMRS (Morley, 2010; Delvaux et al.,  
658 2012). Furthermore, Delvaux et al. (2012) observed dextral strike-slip faulting along the fault  
659 systems bounding the Rukwa Rift, but concluded that the strike-slip event was transitory and was  
660 associated with an early Mesozoic transpressional event that resulted in the inversion of Karoo  
661 sediments. In this study, we observe the existence of a well-defined strike-slip fault bounding the  
662 SW margin of the Mbozi Block that reactivated the Precambrian Mughese Shear Zone. We also  
663 observe lack of present-day activity along the strike-slip fault, and that this fault displaced a buried  
664 mafic dike with at least 500 m of dextral offset.

665 In the absence of chronological data on the mapped dike, we posit that the dike is most-  
666 likely associated with the widespread late-Karoo dike swarms observed in the Luangwa Rift and  
667 Shire Graben (southern Malawi) (Castaing, 1991; Van de Velde and De Waele, 1998). We refer  
668 to this strike-slip fault as the “Mughese Fault”, and the buried dike as the “Chitipa Dike”. The  
669 Chitipa Dike, presented for the first time in this work, may constitute the most excellent record of  
670 strike-slip kinematics along the RNMRS. Although, our results agree with Delvaux et al. (2012)  
671 in that the strike-slip faulting along the RNMRS was short-lived, we suggest that future  
672 geochronological analyses of this intrusion may provide the most-reliable constraint on the timing  
673 of strike-slip faulting event. It is also interesting to note that if the Mughese strike-slip fault is post-  
674 Karoo, its development represents a late reactivation of the Mughese Shear Zone in the evolution  
675 of the RNMRS. However, late reactivation of rift-oblique basement shear zones is not uncommon  
676 in rift basins (e.g., Muirhead and Kattenhorn, 2018).

677 Following the considerations above, we present cartoons of the RNMRS, illustrating the  
678 continuous structural connectivity along the northeast and southwest boundaries guided by the  
679 basement fabrics (Fig. 15B), and possible subsurface geometries and interactions of the domain-  
680 bounding structures (Fig. 15B-E). The inferred dominance of the Ufipa Fault in the northern and  
681 central parts of the Rukwa Rift (Fig. 12) suggest possible truncation of the Lupa Fault at depth,  
682 such that the load of the basin hanging wall block is being carried by the Ufipa Fault (Fig. 15B).  
683 However, seismic data is needed to confirm this interpretation. We illustrate a possible spatial  
684 relationship between the RVP magma pathways and the Mbozi Block bounding faults in Figure  
685 15C. In Figure 15D-E, we show a generalized basin geometry and flip in border fault polarity from  
686 the Malawi Rift North Basin to the Usisya Basin. Overall, we posit that, along the northeastern  
687 boundary of the Mbozi Block transfer zone strain is accommodated by magmatism utilizing pre-

688 existing fault systems, whereas, along the southwestern boundary, strain is accommodated by  
689 dextral strike-slip faulting.

690

#### 691 *5.5. Control of basement fabrics on normal fault geometries*

692 Overall, along the border faults of the Rukwa Rift, we find that strongly-curvilinear normal fault  
693 geometries (in plan-view) occur in three distinct settings. One, in areas where the basement fabrics  
694 describe high curvatures ( $>15^\circ$ ) (e.g., in the Chisi area, northern segment of the Lupa Fault; Fig.  
695 5). Second, in areas of superposition of discordant sets of basement fabrics, in which the overall  
696 fault strike is parallel to one of the sets and relay ramp breach-faults follow the other fabric set that  
697 is oblique to the overall fault strike (e.g., central segment of Ufipa Fault; Fig. 6). Third, in areas  
698 where the faults propagate at high-angle to the strike of the basement fabrics (e.g., in the Kapalala-  
699 Kanga area, southern segment of the Lupa Fault; Fig. 10). In general, along the RNMRS, we find  
700 that in areas where the basement fabrics show low curvatures ( $<10^\circ$ ), the fault segments tend to  
701 describe long, rectilinear geometries with narrow or almost unidentifiable breached-relay zones  
702 (e.g., Southern Ufipa Fault, Fig. 7; Mughese Fault, Fig. 8; Livingstone Fault, Fig. 11). We suggest  
703 that the control of rectilinear ( $<10^\circ$  curvature) basement fabrics on the propagation of normal faults  
704 may result in the development of rectilinear fault segments with greater likelihood of occurrence  
705 of narrow relay ramps and tip-to-tip fault linkage.

706 Curvilinear normal faults have been observed at various scales and at different extensional  
707 tectonic settings (Fossen and Rotevatn, 2016). However, the first order curvilinear normal faults  
708 are typically characterized by segment boundaries with salients (cusps) that plunge basin-ward  
709 e.g., Salt-lake salient and Transverse Mountain salients of the Wasatch Fault in Utah (Fig. 16A),  
710 and the Gullfaks salient in the North Sea (Fig. 16B) (Fossen and Rotevatn, 2016). Also, the

711 reported curvilinear faults show characteristic basin-ward concave geometries. However, the  
712 South Oquirrh Mountains normal fault zone, although curvilinear (Wu and Bruhn, 1994), exhibits  
713 striking basin-ward convex geometry in which the cusps point into the footwall of the fault (Fig.  
714 16A). Wu and Bruhn (1994) suggested that convex curvilinear geometry of the South Oquirrh  
715 Mountains normal fault zone developed by sequential propagation of the fault into its foot-wall,  
716 guided by linkage across smaller en-echelon faults created by the lateral shear components at the  
717 tips of the propagating fault. Here, in the Rukwa Rift, we observe both convex- and concave-  
718 curvilinear normal fault geometries along the Ufipa and Lupa Faults. The central Ufipa Fault (Fig.  
719 6) and southern Lupa Fault (Kapalala-Mwambani area in Fig. 10A-C) exhibit convex-curvilinear  
720 normal fault geometries, whereas the northern Ufipa Fault and the Chisi Fault demonstrate  
721 concave-curvilinear fault geometries (linked at the Chisi salient) (Fig. 5). Also, we find striking  
722 similarities between the concave- and convex-curvilinear fault geometries of the Rukwa Rift (Fig.  
723 16C) with those in the southern Malawi Rift (Fig. 16D), the Jurassic sedimentary sequence of the  
724 northern North Sea rift (Gullfaks area) (Fig. 16B), and the Provo-Salt Lake City area (Fig. 16A).  
725 As show in Figure 16D, the segments of the Bilila-Mtakataka Fault in southern Malawi Rift present  
726 excellent examples of convex-curvilinear normal fault geometries (Jackson and Blekinsop, 1997).  
727 Recent studies on the relationships between the basement fabrics and the Bilila-Mtakataka Fault  
728 segments (Johnson et al., 2018; Hodge et al., 2018) show that some of the segments appear to align  
729 with the distributed basement fabrics, while others cut across the basement fabrics.

730         Based on the observations above, we present conceptual models for the control of various  
731 configurations of pre-existing basement fabrics on the development of curvilinear normal fault  
732 plan-view geometries (Fig. 17). We show how discrete and distributed basement fabrics and  
733 combinations of the two categories of fabrics can influence the plan-view geometry of normal

734 faults. However, there is need to better understand (1) the influence of the basement fabrics on the  
735 geometries of curvilinear normal faults in 3-dimensions, (2) the influence of the extension  
736 direction on the development of the observed curvilinear normal faults in areas where the basement  
737 fabric present mechanical anisotropy.

738         Although, Fossen and Rotevatn (2016) provide evidence of subsidiary short-cut faulting  
739 across a salient, suggesting an impending evolution of concave-curvilinear faults into rectilinear  
740 faults, it is not yet clear if the model applies to convex-curvilinear normal faults since the two  
741 styles of faults are geometrically different. However, the synthetic Bilila-Mtakataka and the  
742 Chirobwe-Ncheu Faults (Fig. 16D) in southern Malawi Rift may provide some insight. Since the  
743 Chirobwe-Ncheu Fault is older than the Bilila-Mtakataka Fault (Jackson and Blekinsop, 1997), the  
744 rectilinear geometry of the Chirobwe-Ncheu Fault suggests that the apices of convex curvilinear  
745 segments may likewise eventually get breached to form more-rectilinear fault segments.  
746 Conversely, we observe the opposite of this model along the Lupa Fault, where the more-  
747 rectilinear northern Lupa Fault has accommodated much less strain compared to its curvilinear  
748 southern segment which has the most strain within the Rukwa Rift (Morley et al., 1992). Therefore,  
749 we suggest that although the model of temporal progression from a curvilinear to rectilinear fault  
750 geometry may apply to some large normal faults, it may not apply to others.

751

## 752 *5.6. Rift Bifurcation*

753         The basin scale splaying of the Rukwa Rift around the Mbozi Block into the Musangano  
754 and Songwe Troughs (Fig. 1B) obviously represents a smaller-scale of rift bifurcation when  
755 compared to the continental scale bifurcation of rift systems around microplates. Examples of such  
756 continental-scale rift bifurcation include the branching of the East African Rift around the



757 Tanzania microplate into the western and eastern branches (Fig. 1A; e.g., Rosendahl, B.R., 1987;  
758 Versfelt and Rosendahl, 1989), the Red Sea Rift around the Sinai microplate into the Gulf of Suez  
759 Rift and Dead Sea Transform, and the South Atlantic Rift around the Sergipe microplate into the  
760 Tucano-Recôncavo Rift and Sergipe-Alagoas Transform (e.g., Szatmari and Milani, 1999) (Figs.  
761 18A-C). Based on scale distinction, we therefore refer to the continental rift-system scale  
762 bifurcation as first (1<sup>st</sup>) order rift bifurcation (Figs. 18A-C) and the rift-basin scale bifurcation as  
763 second (2<sup>nd</sup>) order rift bifurcation (Fig. 18D-F). Similar to the Rukwa Rift, 2<sup>nd</sup> order rift  
764 bifurcations are common along the East African Rift System. Examples include the Southern  
765 Malawi Rift bifurcation around the Shire Horst, the Shire Graben bifurcation around the  
766 Namalambo Horst, and the Albertine Graben bifurcation around the Rwenzori Block (Fig. 18B;  
767 e.g., Castaing, 1991; Koehn et al., 2008; Lao-Davila et al., 2015; Xue et al., 2017).

768         Regardless of scale, numerical models have showed that inherited structural heterogeneity  
769 and lateral strength variations are key controls on rift bifurcation (e.g., Brune and Autin, 2013;  
770 Brune et al., 2017). However, it appears that 1<sup>st</sup> order bifurcations commonly occur at the tip of  
771 pre-existing microcratonic blocks along the path of propagation of a continental rift system (e.g.,  
772 Fig. 18A). Also, 2<sup>nd</sup> order bifurcations appear to occur at the transfer zones between approaching  
773 rift segments, possibly due to a high tendency for the development of interfingering fault blocks  
774 in the transfer zones between colinear approaching rift segments (Morley, 1995) and lateral  
775 rotation of the trapped blocks in the transfer zones between overlapping approaching rift segments  
776 (Koehn et al., 2008).

777         It is possible that the bifurcation of the Rukwa Rift around the Mbozi Block is related to  
778 the location of the block within the transfer zone of the colinear approaching Rukwa and North  
779 Malawi Rift segments. However, we suggest that the basement fabrics of the Ubendian Belt around

780 the Mbozi Block transfer zone could be playing a complementary role in facilitating and guiding  
781 the intra-rift bifurcation of the Rukwa Rift around the block. Our filtered aeromagnetic map (Fig.  
782 4B) shows that the block is dominated by a WNW-ESE and N-S fabrics. According to Daly (1988),  
783 the Meta-basites and intermediate granulites and quartzites of the Mbozi Block are characterized  
784 by lineations that trend NE-SW. These observations, however, suggest that the Mbozi Block  
785 fabrics strike at oblique to high-angles to the trend of the colinear fabrics of the basement terranes  
786 bounding the Mbozi Block (Katuma-Upangwa Terranes to the northeast, and those of the Ufipa  
787 Terrane to the southwest) and the main rift-bounding faults (the Lupa, Ufipa, Livingstone and  
788 Mughese Faults) (Fig. 15A). Therefore, we suggest that the colinear fabrics of the basement  
789 terranes surrounding the Mbozi Block which are already controlling the propagation and linking  
790 of the rift-bounding faults may be playing a significant role in guiding the bifurcation of the Rukwa  
791 Rift around the Mbozi Block (Figs. 4B, 7, 8 and 11).

792

## 793 **6.0 CONCLUSIONS**

794 Our topographic analyses of the morphology of the RNMRS and detailed study of the  
795 relationships between the pre-existing basement fabric and rift-related faults provide, for the first  
796 time, evidence supporting the coupling of the Rukwa and North Malawi Rift. Our topographic  
797 analyses in the Rukwa Rift suggest that the Ufipa Fault is the present-day active border fault of  
798 the rift. We find that the Ufipa fault is the dominant topographic feature in the northern part of the  
799 RNMRS and diminishes as it encounters the Mbozi block where it becomes a strike slip fault  
800 (Mughese Fault), at which point the border fault polarity flips and the Livingstone Fault is the  
801 dominant fault in the southern part of the RNMRS.

802 Further, we demonstrate the continuity structures along the northeastern and southwestern  
803 margins of the RNMRS. We show that this structural connectivity across the Mbozi Block transfer  
804 zone between the rifts is guided by the pre-existing Precambrian terrane fabrics and associated  
805 shear zones. We show that the coupling of the RNMRS along the northeastern boundary of the  
806 Mbozi Block transfer zone is accommodated by magmatism along the linking faults, whereas,  
807 coupling along the southwestern boundary is accommodated by strike-slip faulting. Overall, we  
808 suggest that the continuation of the boundary faults along the RNMRS, and their alignment with  
809 colinear Precambrian basement fabric and shear zones indicate the influence of the pre-existing  
810 basement structures on the coupling and amalgamation of approaching colinear rift segments. On  
811 the basin-scale bifurcation of the Rukwa Rift, we infer that the discordance of the basement fabrics  
812 within the Mbozi Block transfer zone to those of the basement terranes bounding it may have  
813 facilitated the development of intra-rift bifurcation of the rift around the transfer zone.

814 Furthermore, we show the influence of pre-existing basement fabrics on the development  
815 of the RNMRS as evidenced in the geometry, termination and kinematics of the rift-bounding fault  
816 segments. Our observations suggest that curvilinear normal fault geometries developed in areas  
817 where the basement fabrics are either curvilinear, composed of superposed sets of differently-  
818 orientated fabrics, or not favorably oriented to the extensional stress field. Whereas, long,  
819 rectilinear fault geometries with narrow or almost unidentifiable breached-relay zones developed  
820 in areas where the pre-existing basement fabrics are roughly rectilinear, suggesting the greater  
821 likelihood of occurrence of tip-to-tip linkage of fault segments.

822 Finally, we present the existence of a buried Pre-Cenozoic strike-slip-faulted mafic dike,  
823 which we suggest is potentially the most excellent record of strike-slip kinematics along the  
824 RNMRS. We further suggest that future geochronological analyses of this intrusion may provide

825 the most-reliable constraint on the timing of the controversial strike-slip faulting event along the  
826 RNMRS.

827

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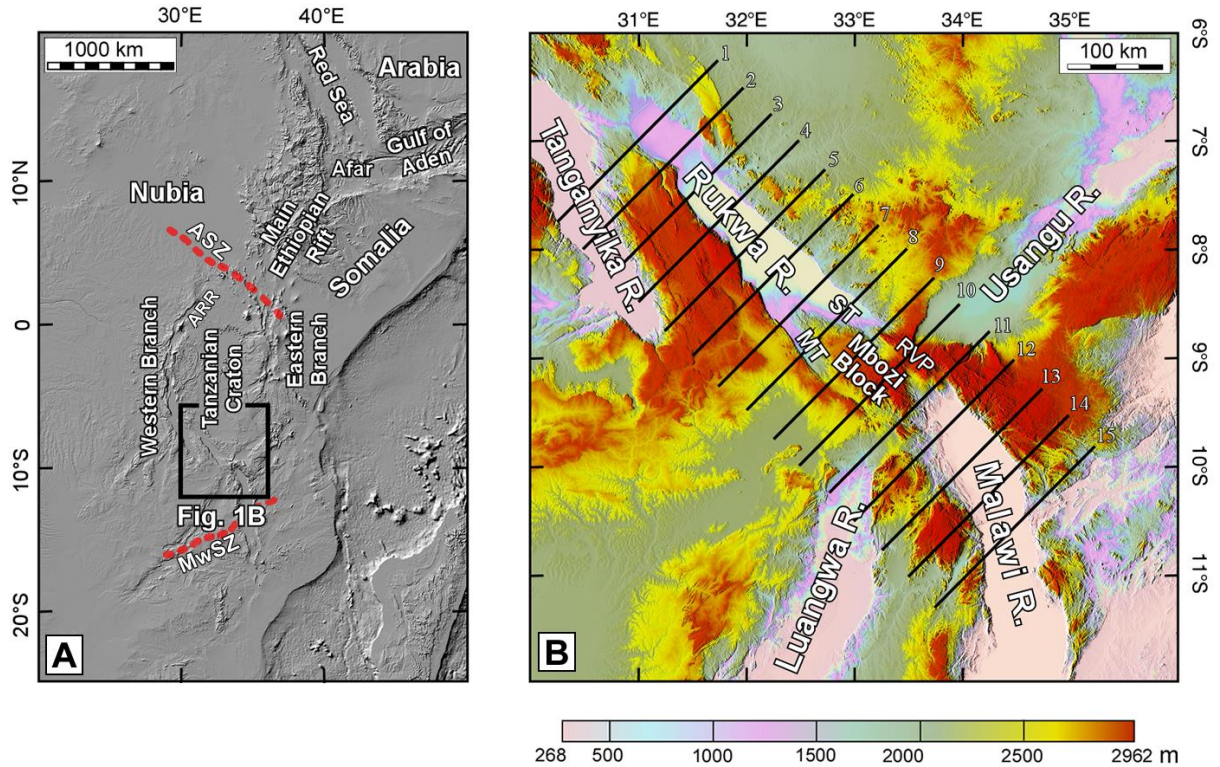
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1093 Fig.1. (A) Topographic map of the East African Rift System, showing the segments of the rift  
1094 system and the location of the Rukwa-North Malawi Rift Segment (RNMR) (black square). (B)  
1095 Digital Elevation Model (DEM) of the RNMR showing the different domains. Solid black lines  
1096 represent topographic profile lines shown in Figure 3. ARR= Albertine-Rhino Rift, ASZ= Aswa  
1097 Shear Zone, MT= Musangano Trough, MwsSZ= Mwembeshi Shear Zone, RVP= Rungwe Volcanic  
1098 Province, ST= Songwe Trough.

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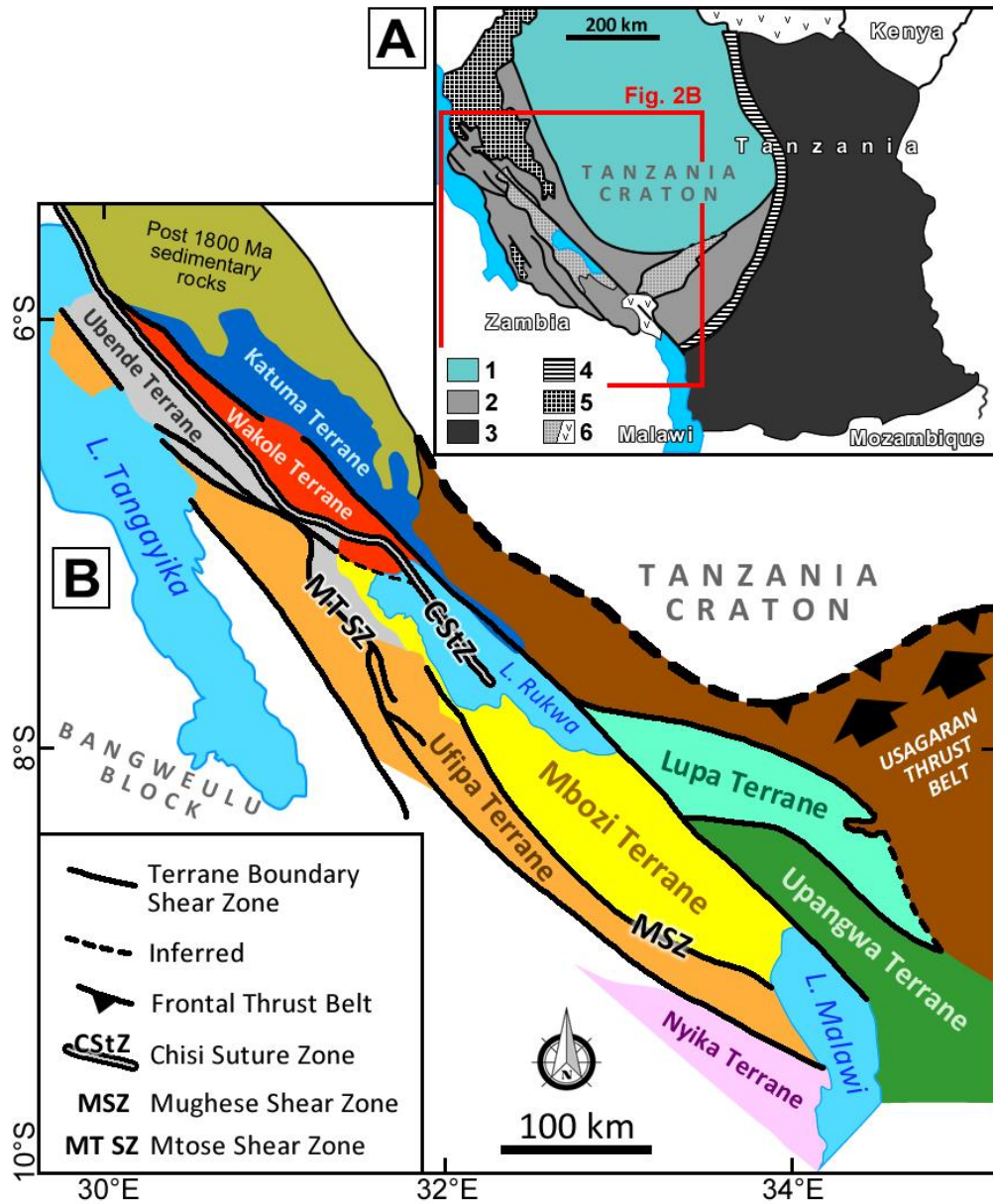
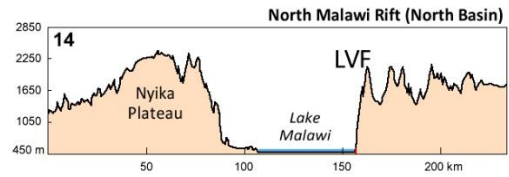
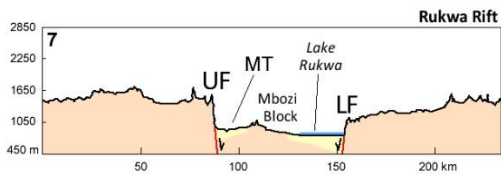
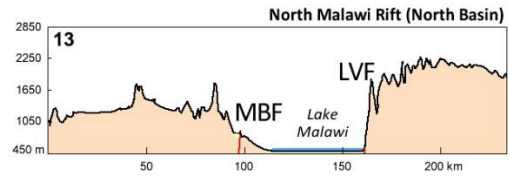
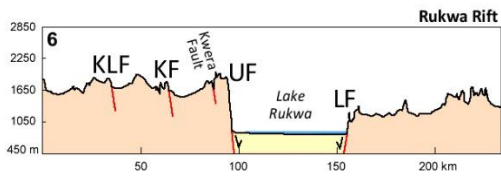
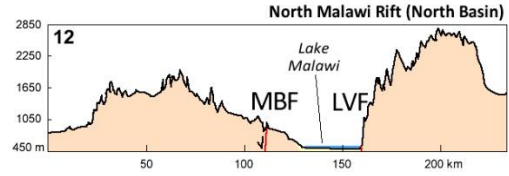
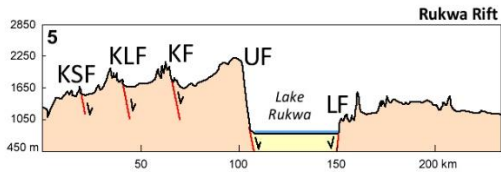
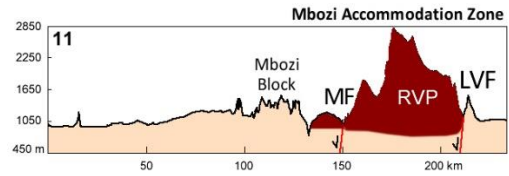
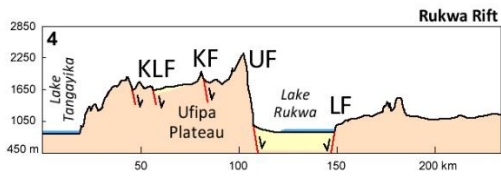
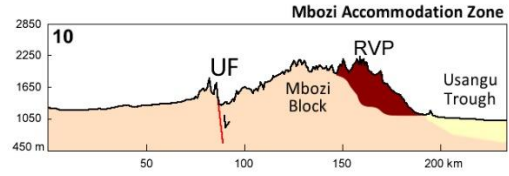
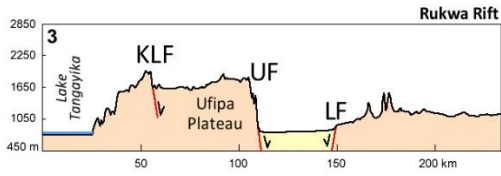
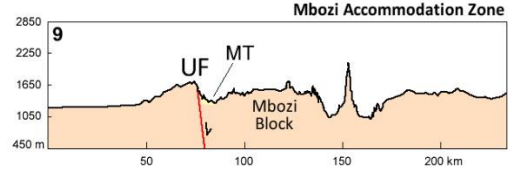
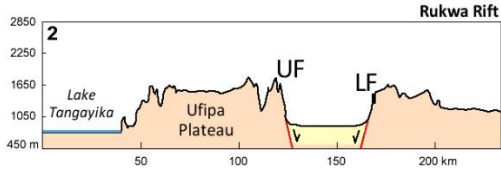
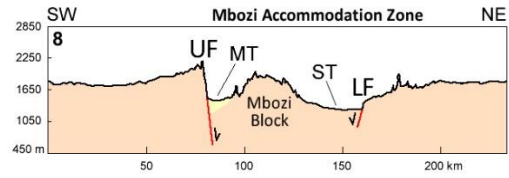
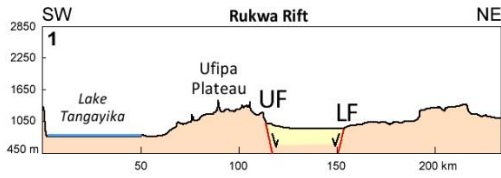
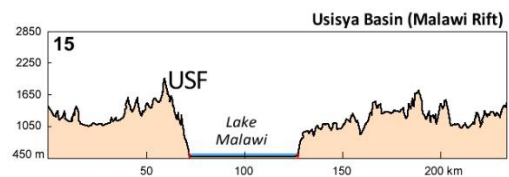


Fig. 2. (A) Precambrian domains around the Tanzanian Craton (modified after Theunissen et al., 1996; Boven et al., 1999; Fernandez-Alonso et al., 2001; Boniface and Schenk, 2012; Delvaux et al., 2012). 1 = Archean craton; 2 = Paleoproterozoic Usagaran and Ubendian orogenic belts; 3 = Mozambique orogenic belt; 4 = western limit of Pan-African influence; 5 = Meso and/or Neoproterozoic sediments (*only for the Ubendian Belt region*); 6 = Phanerozoic volcanics and sedimentary rocks. (B) Regional geological map of southwest Tanzania showing the terrane structure of the Ubendian orogenic belt within which the Rukwa-Malawi Rift Segment (RNMRS) developed.



- Normal Fault
- Cenozoic Sediments
- Rungwe Volcanics
- Precambrian Basement



1162 Fig. 3. Topographic profiles across the Rukwa - North Malawi Rift segment. Profile numbers  
1163 correspond to the profiles in Figure 1B. KLF = Kalambo Fault, KF = Kanda Fault, KSF = Kasanga  
1164 Fault, LF = Lupa Fault, LVF = Livingstone Fault, MB = Mbozi Block, MBF = Mbiri Fault, MF =  
1165 Mbaka Fault, MT = Musangano Trough, RVP = Rungwe Volcanic Province, ST = Songwe  
1166 Trough, UF = Ufipa Fault, USF = Usisya Fault.  
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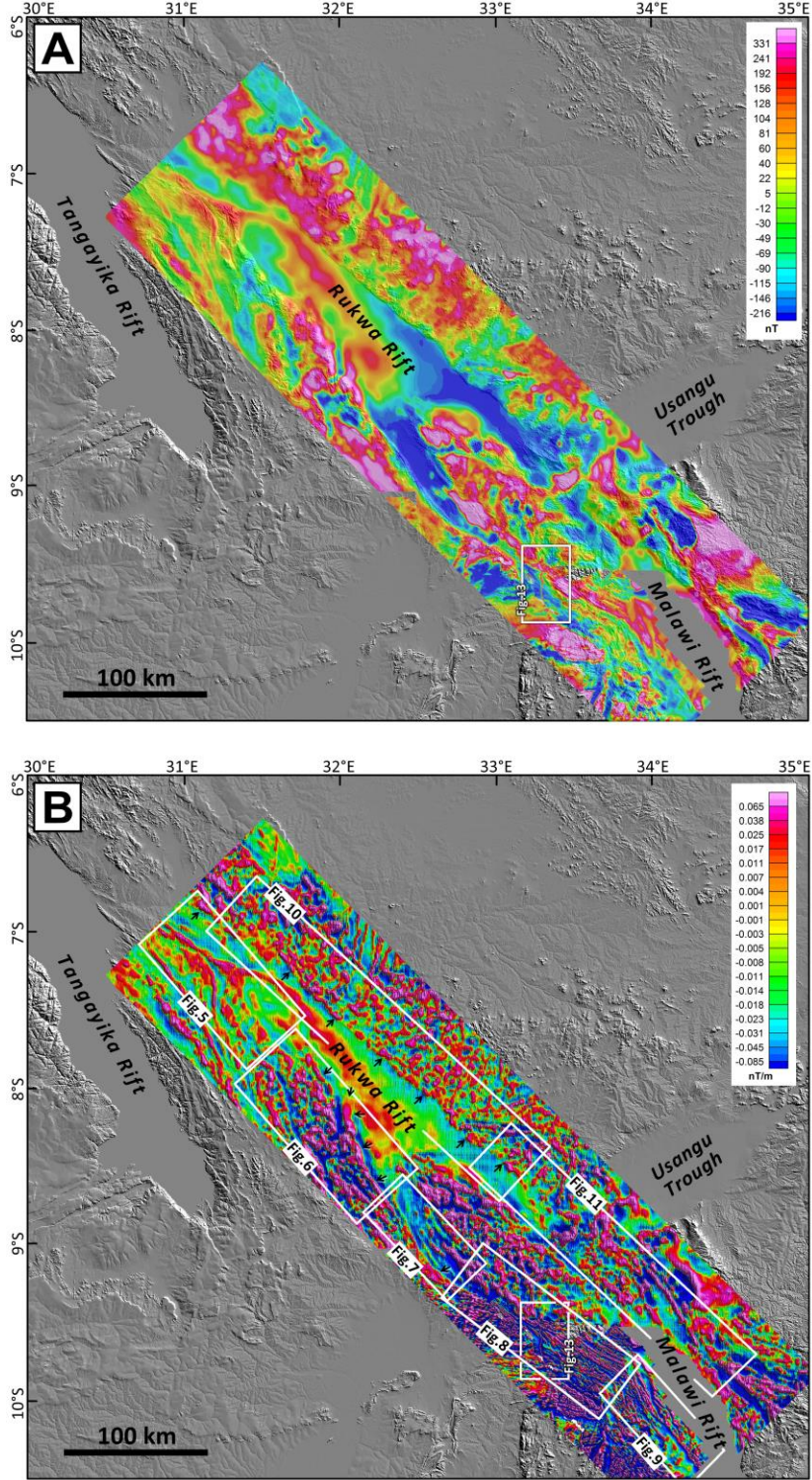


Fig. 4. (A) The reduced to pole Total Magnetic Intensity (RTP-TMI) map of the Rukwa-North Malawi Rift area, draped over the topographic digital elevation model of SW Tanzania. (B) The 1<sup>st</sup> vertical derivative map of the RTP-TMI map of the Rukwa-North Malawi Rift area draped over the topographic digital elevation model.

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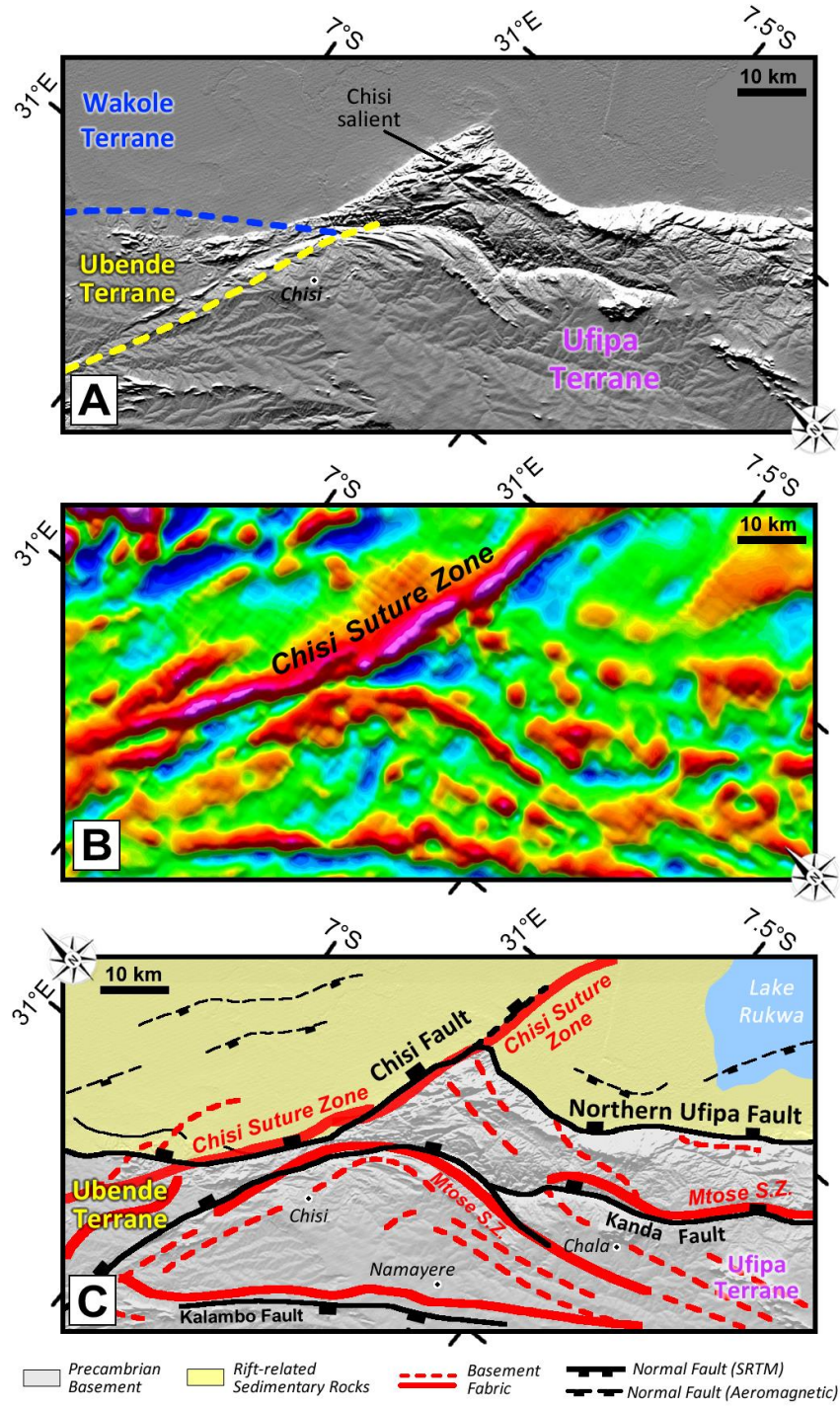


Fig. 5. Northernmost part of the Ufipa Fault, the SW boundary fault of the Rukwa Rift. Topographic digital elevation model in the top panel (A), the vertical derivative of the magnetic data in the middle panel (B), and a structural interpretation in the bottom panel (C).

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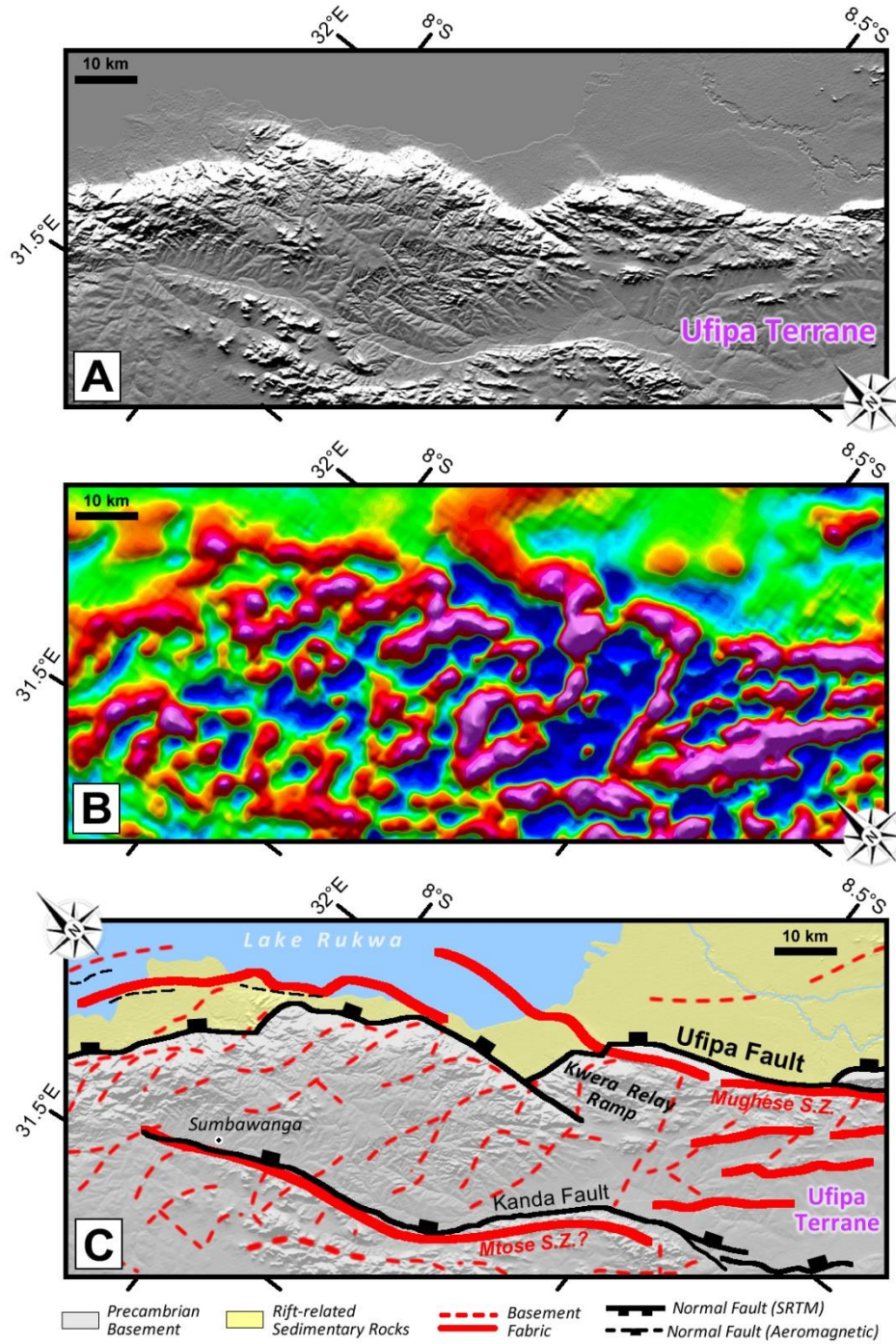


Fig. 6. Central segment of the Ufipa Fault, SW boundary of the Rukwa Rift. Topographic digital elevation model in the top panel (A), the vertical derivative of the magnetic data in the middle panel (B), and a structural interpretation in the bottom panel (C).

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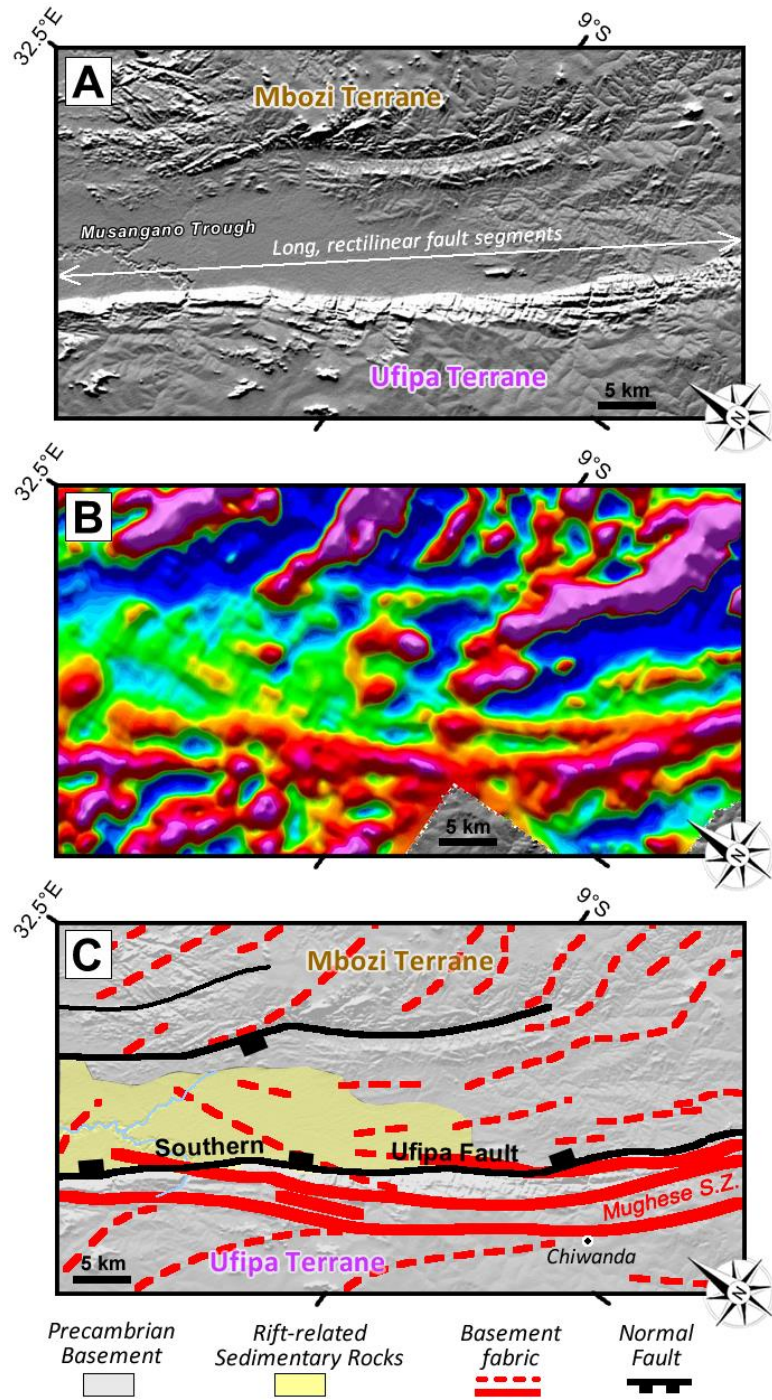


Fig. 7. The Musangano Trough part of the SW boundary of the Rukwa Rift. Topographic digital elevation model in the top panel (A), the vertical derivative of the magnetic data in the middle panel (B), and a structural interpretation in the bottom panel (C).

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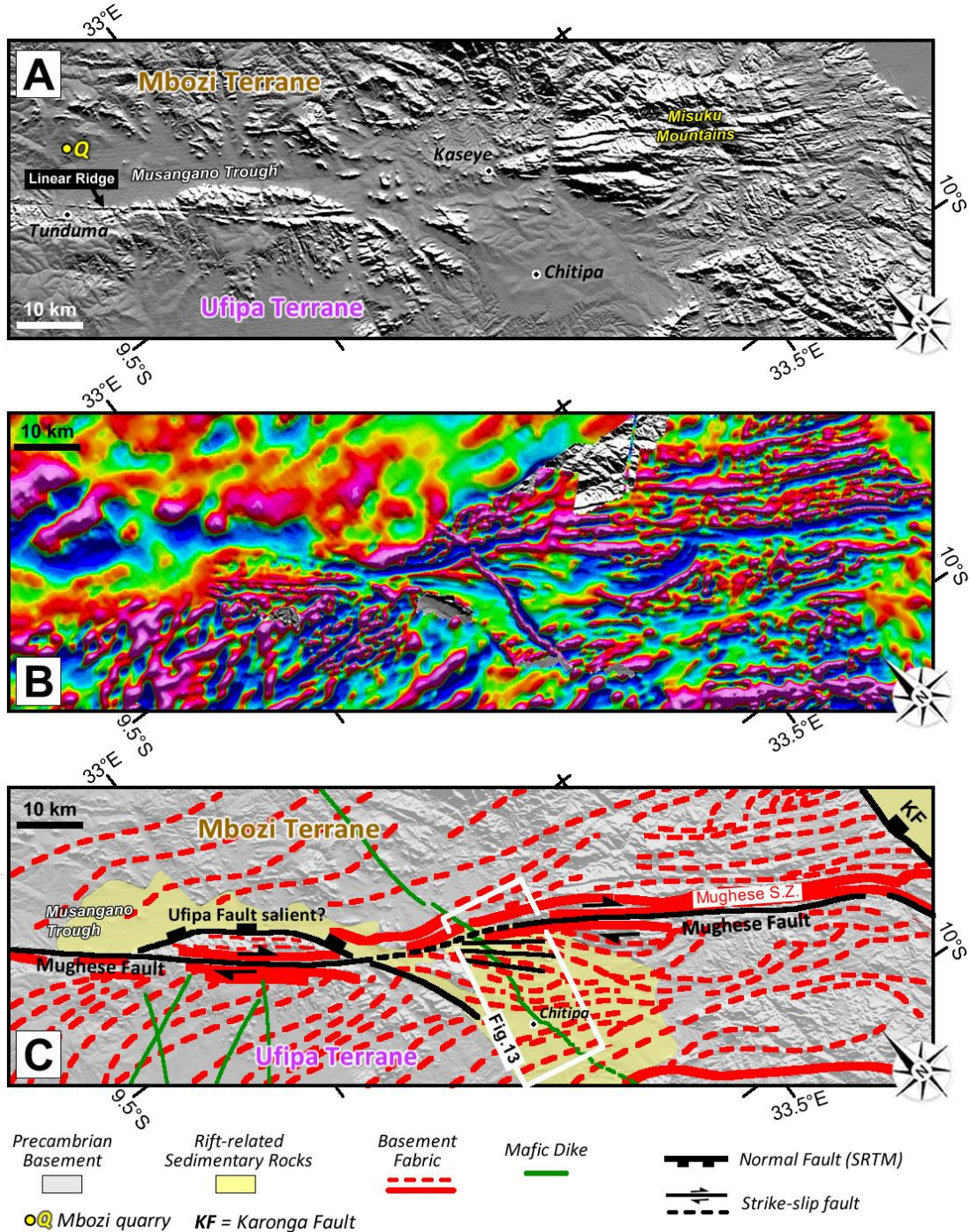
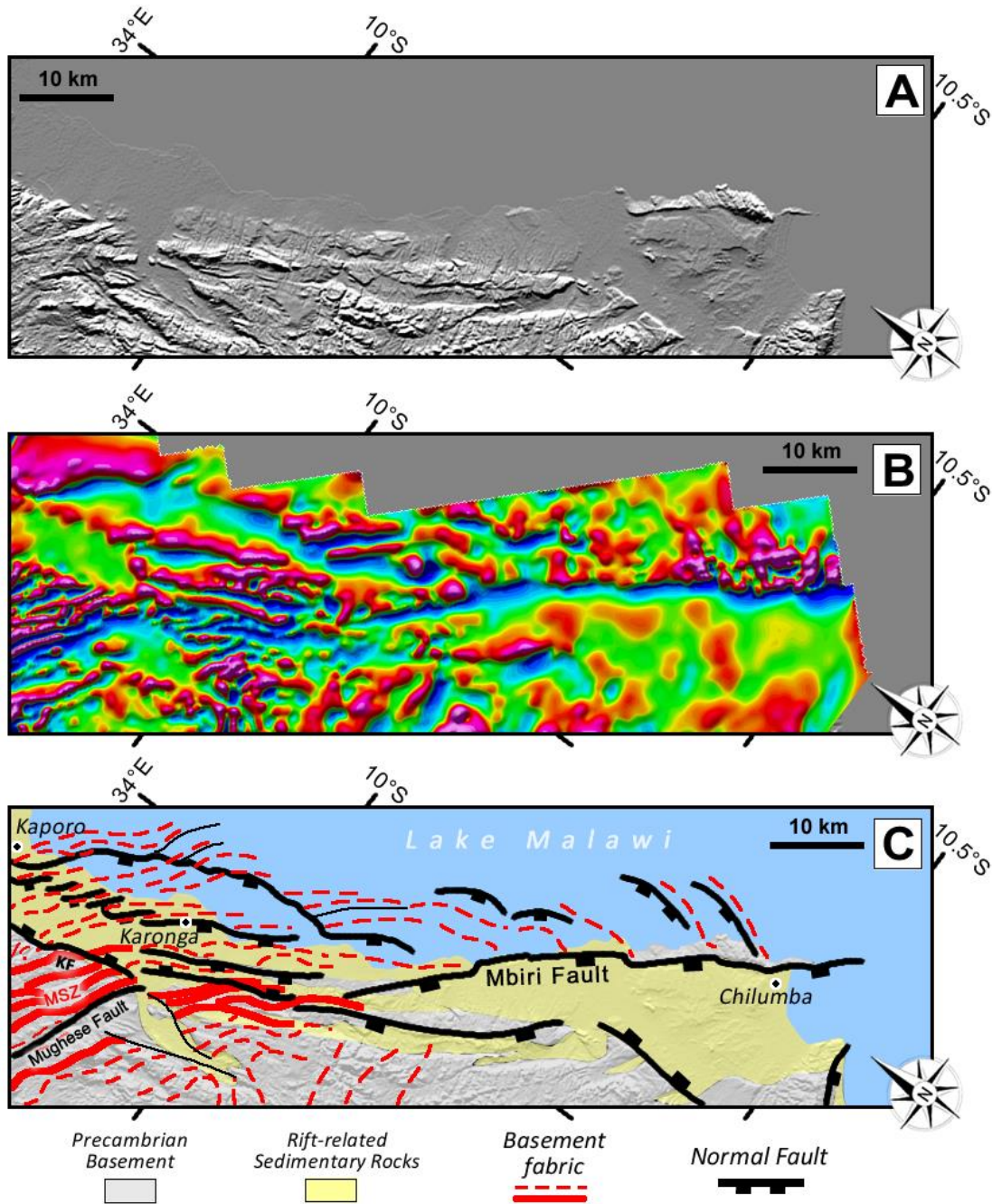


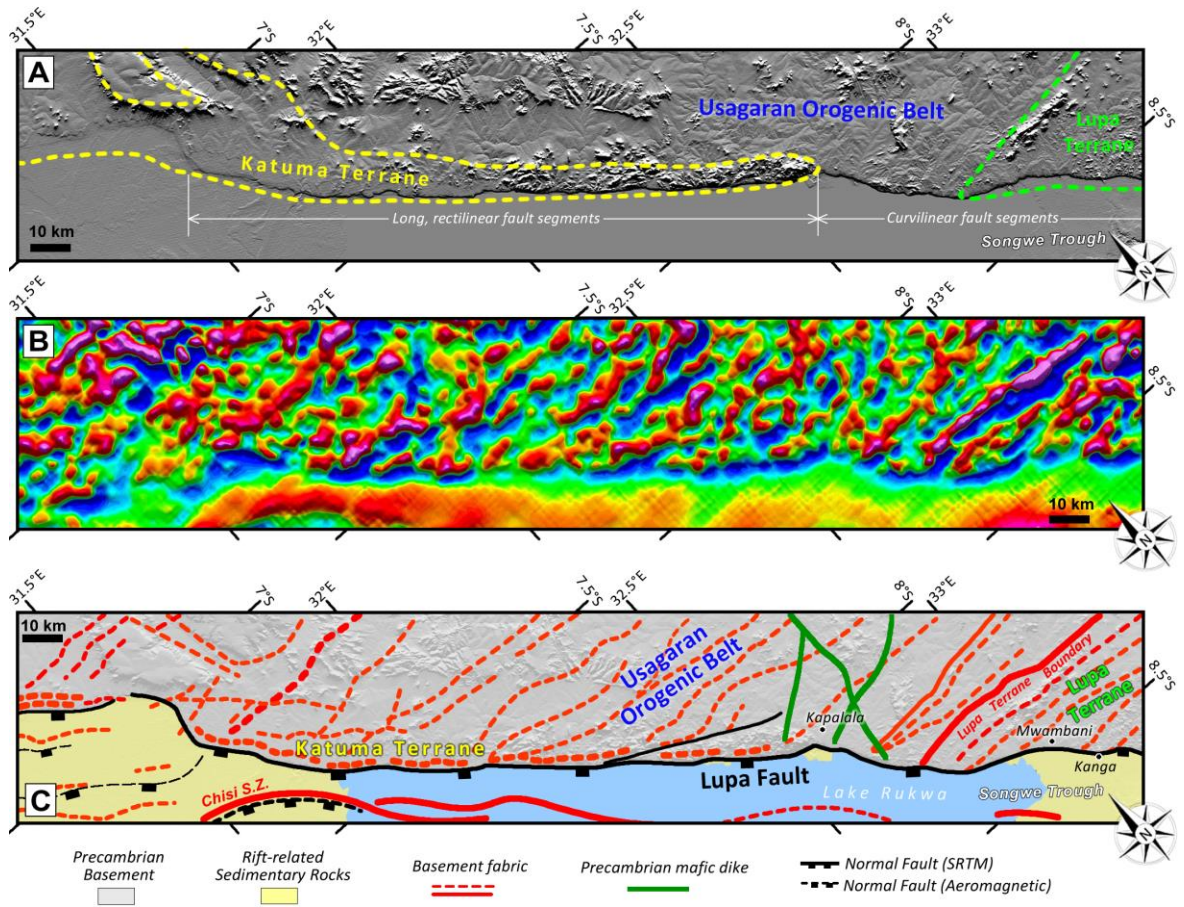
Fig. 8. The SW margin of the Mbozi Block. Topographic digital elevation model in the top panel (A), the vertical derivative of the magnetic data in the middle panel (B), and a structural interpretation in the bottom panel (C).





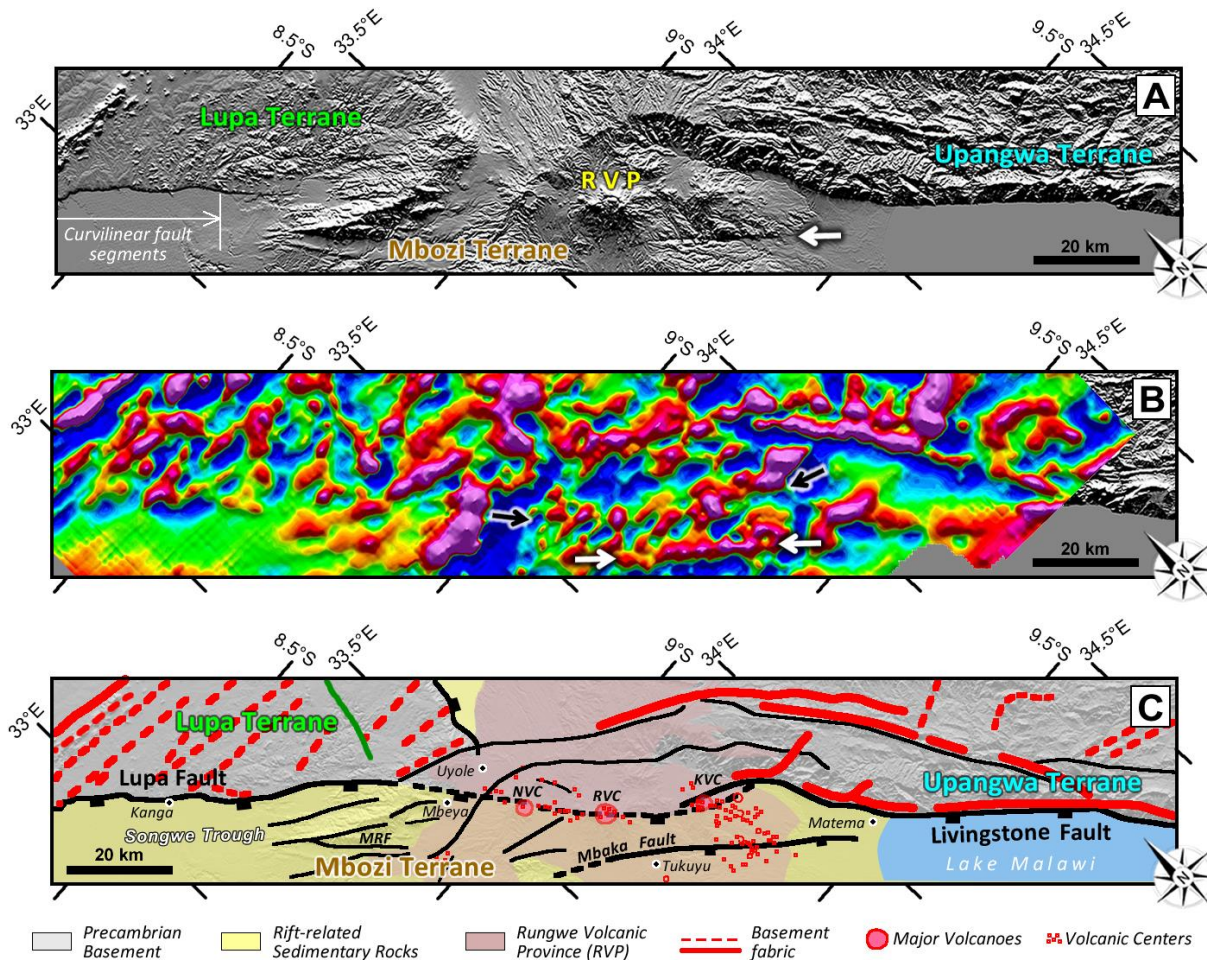
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Fig. 9. The SW margin of the North Malawi Rift Basin (Karonga area). Topographic digital elevation model in the top panel (A), the vertical derivative of the magnetic data in the middle panel (B), and a structural interpretation in the bottom panel (C). MSZ = Mughese Shear Zone, KF = Karonga Fault. Fault and basement fabric interpretations from Kolawole et al. (2018).



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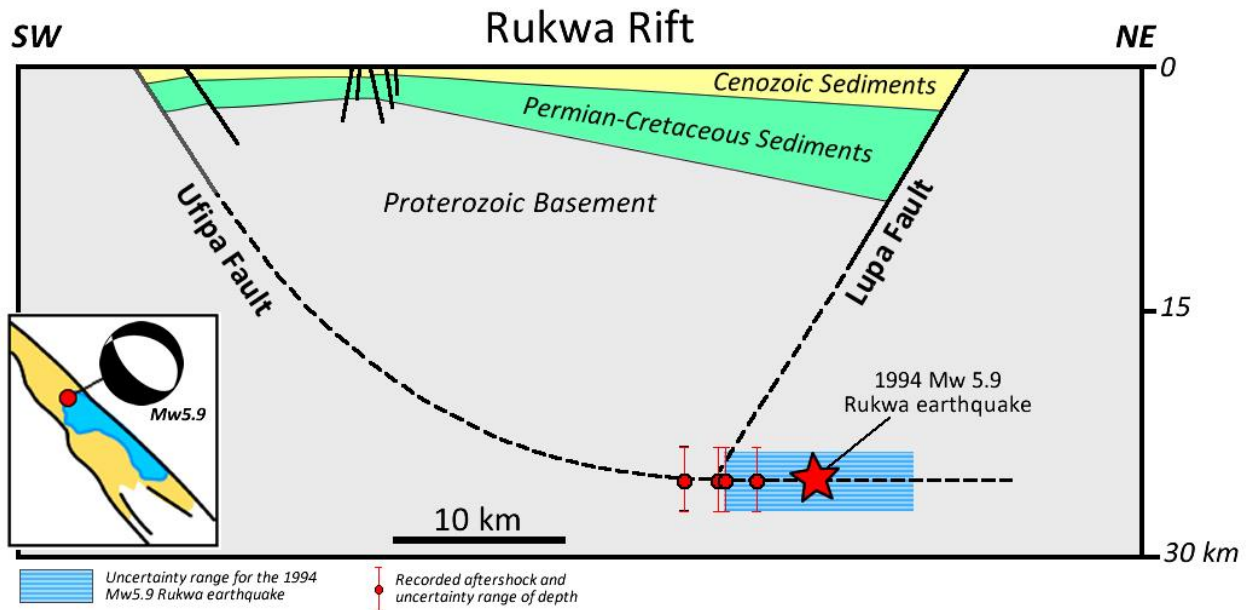
Fig. 10. The northern section of the Lupa Fault, the NE boundary fault of the Rukwa Rift. Topographic digital elevation model in the top panel (A), the vertical derivative of the magnetic data in the middle panel (B), and a structural interpretation in the bottom panel (C).



1403  
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 1406 Volcanic Province) and a section of the Livingstone Fault (NE border fault of the North Malawi  
 1407 Rift). Topographic digital elevation model in the top panel (A), the vertical derivative of the  
 1408 magnetic data in the middle panel (B), and a structural interpretation in the bottom panel (C). KVC  
 1409 = Kyejo Volcanic Center; NVC = Ngozi Volcanic Center; RVC = Rungwe Volcanic Center.  
 1410 Volcanic centers from Fontijn et al. (2010, 2012).

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Fig. 12. Generalized geometrical relations of stratigraphic units and normal faults of the Rukwa rift, showing thickening of Cenozoic sediments towards both the Lupa and Ufipa border faults (modified after Zhao et al., 1997).

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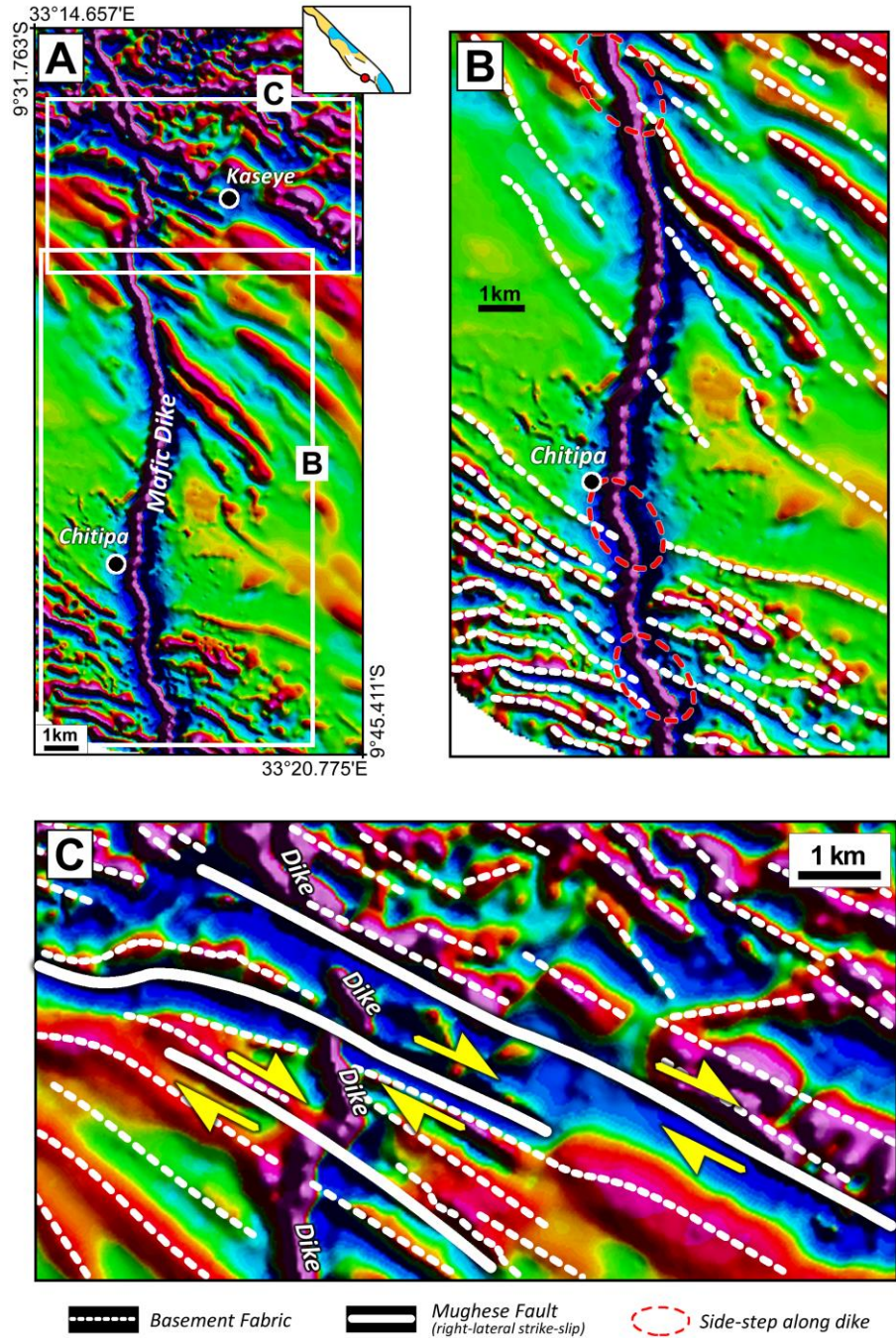


Fig. 13. (A) 1<sup>st</sup> vertical derivative of the aeromagnetic data covering the Kaseye-Chitipa area along the SW margin of the Mbozi Block (see location in top-right inset map, Figures 4A-B and 8C). (B) Close-up of the central and southern segments of a buried mafic dike (the “Chitipa Dike”) showing side-stepping segments that coincide with pre-existing basement fabric. (C) Close-up of the northern segment of the dike showing right-lateral offsets by the continuation of the Ufipa Fault. This strike-slip fault segment is here-in referred to as the Mughese Fault.

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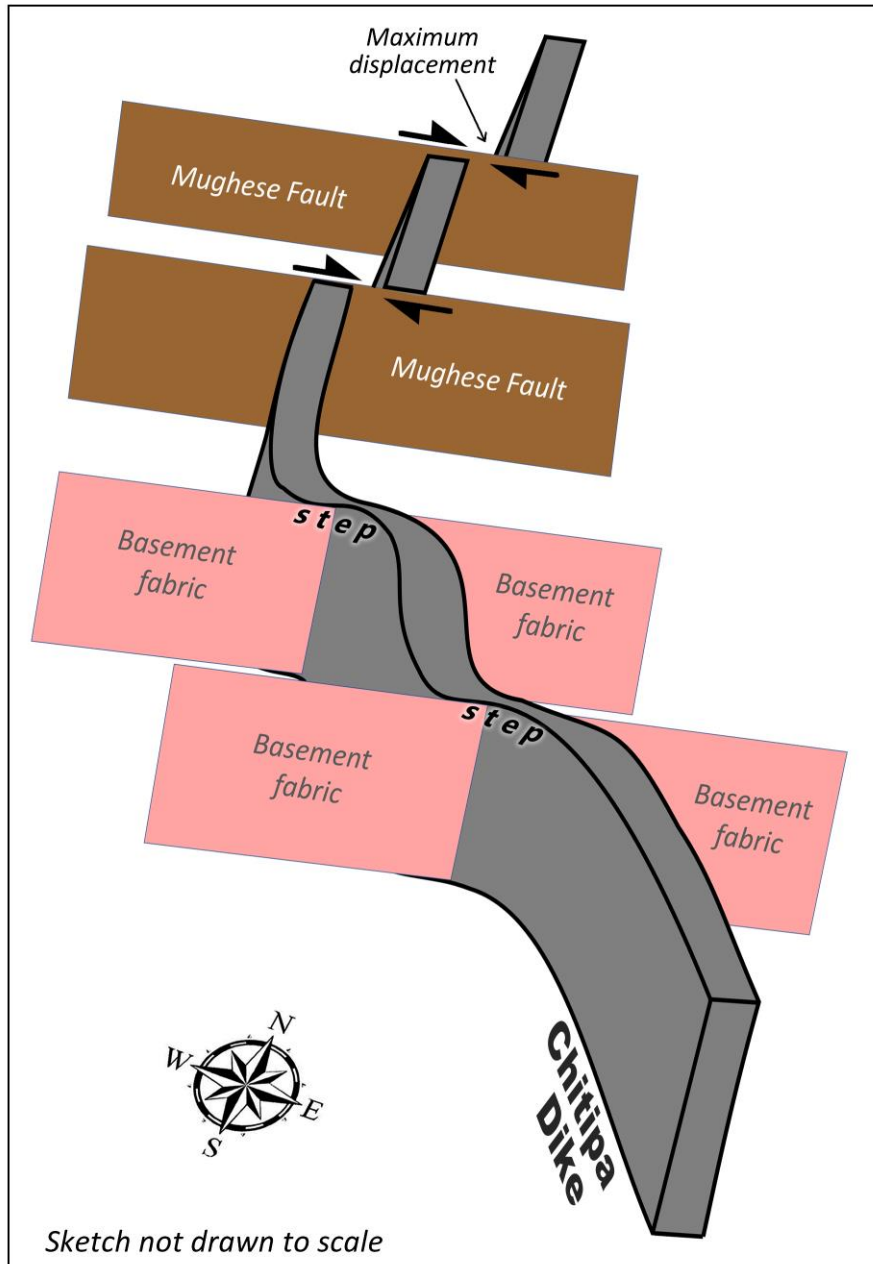
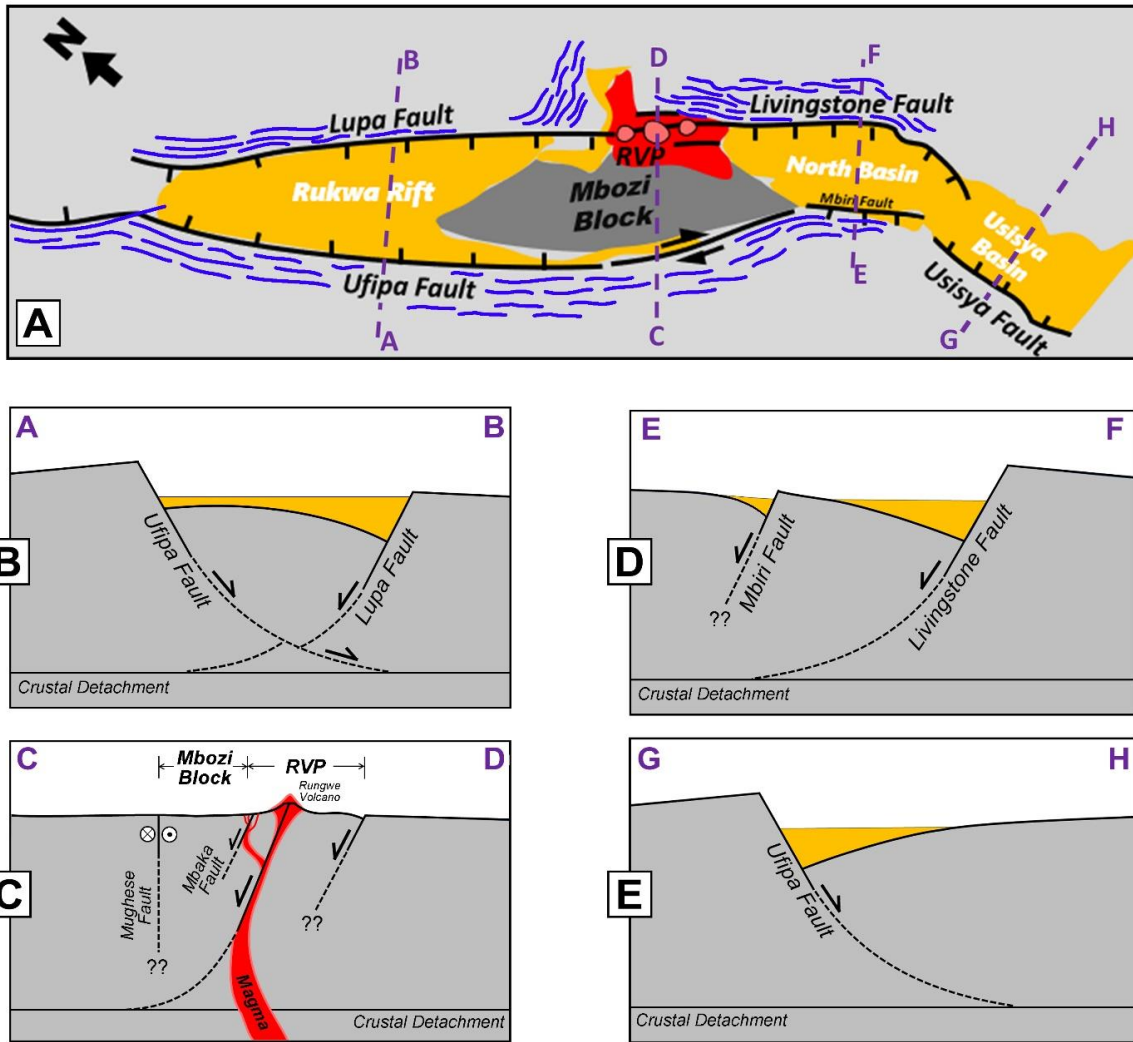


Fig. 14. 3-dimensional (3-D) conceptual model of the geometry of the interpreted dike (the “Chitipa Dike”) and its interactions with the pre-existing basement fabric and the post-emplacment Mughese strike-slip fault offset.



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 1544 Fig. 15. (A) Generalized cartoon (map view) of the Rukwa-North Malawi Rift Segment (RNMRS)  
 1545 illustrating the continuous structural connectivity along the northeast and southwest boundaries,  
 1546 guided by the basement fabric. Black solid line = fault, blue solid line = basement fabric. RVP =  
 1547 Rungwe Volcanic Province. (B-E) Cross-section cartoons across the segments of the RNMRS,  
 1548 illustrating the possible subsurface geometries and interactions of the domain-bounding structures.  
 1549 LLF = Livingstone-Lupa Fault.

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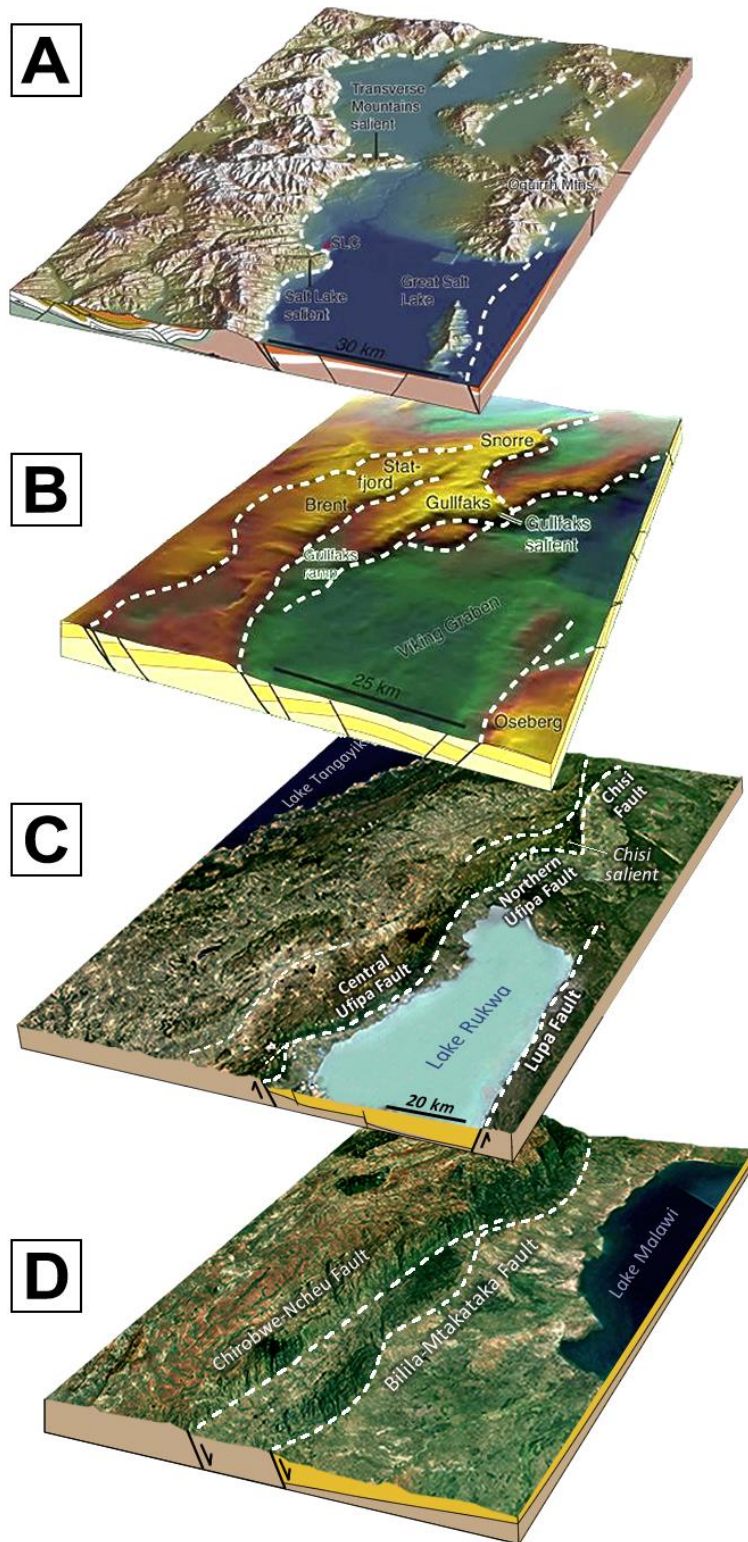


Fig. 16. (A-B) The Wasatch Fault in the Salt Lake area, Utah, and the first-order faults in the northern North Sea (base Cretaceous unconformity) showing concave-curvilinear fault geometries (modified after Fossen and Rotevatn, 2016). (C) Strikingly similar Concave-curvilinear fault geometry occurs in the northern Ufipa Fault and Chisi Fault in the Rukwa Rift. However, the Central Ufipa Fault shows convex-curvilinear fault geometry. (D) The Bilila-Mtakataka Fault also shows excellent convex curvilinear fault geometries.

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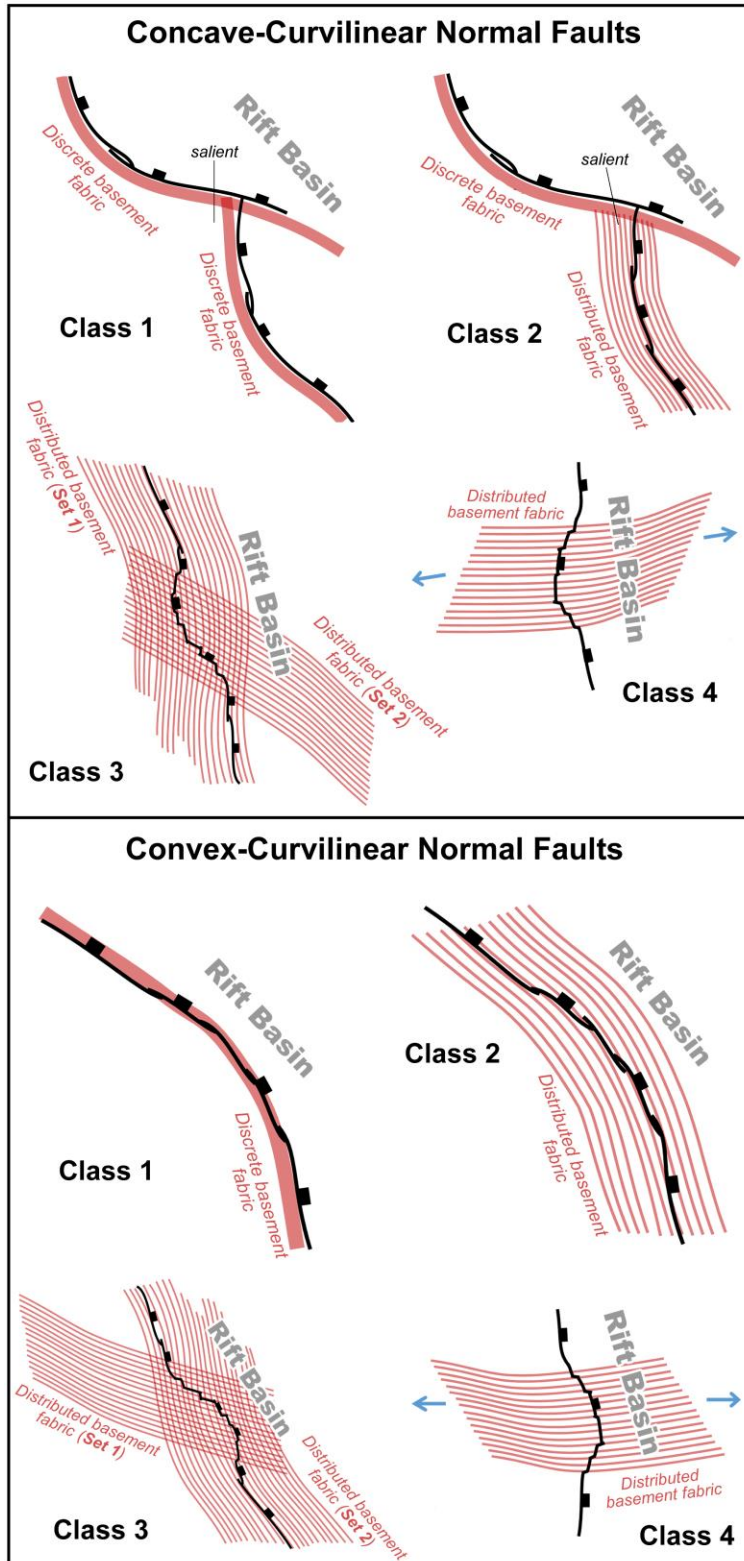


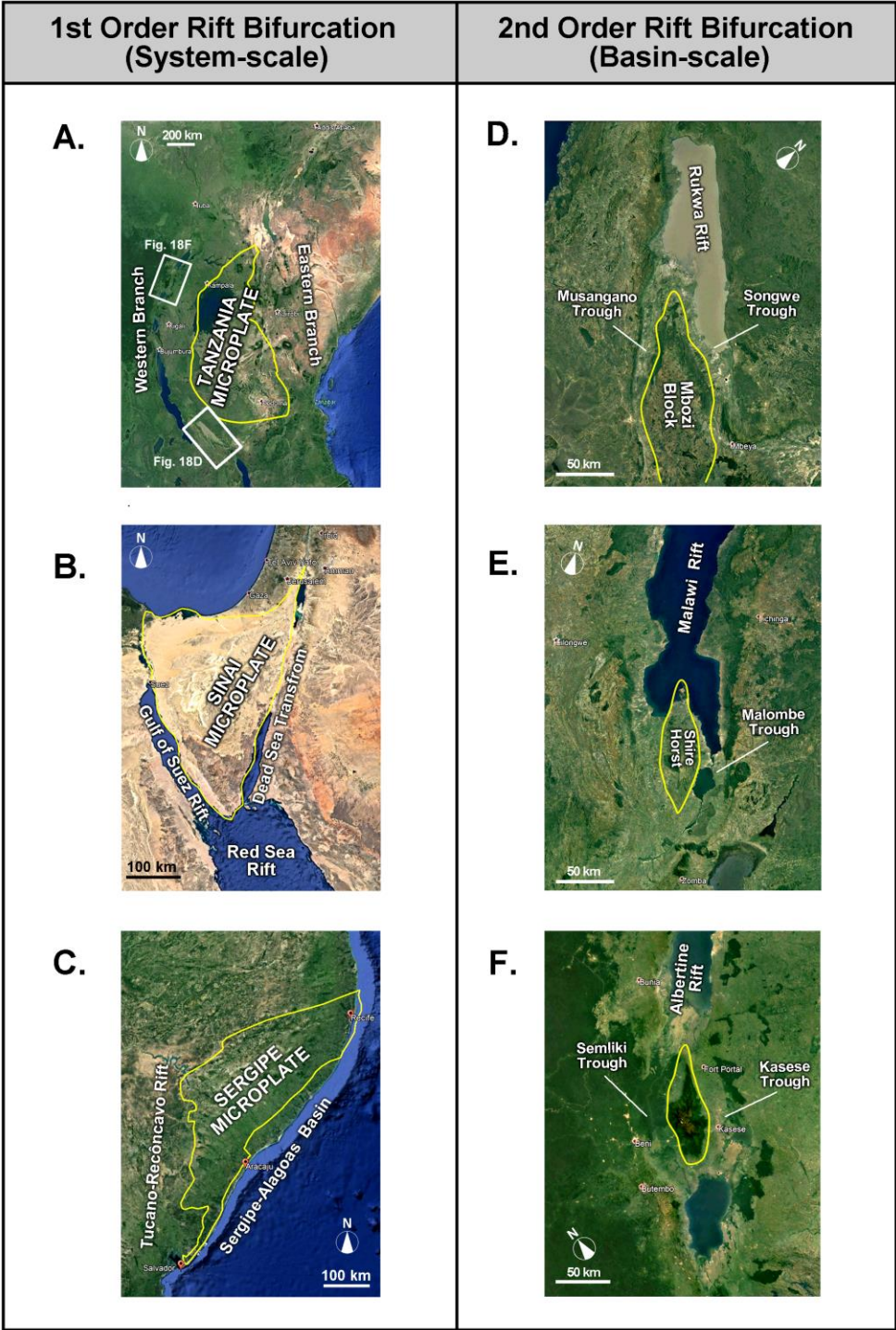
Fig. 17. Models illustrating the control of varying configurations of pre-existing basement fabrics on the development of concave- and convex-curvilinear normal fault plan-view geometries. These models are based on the observations from the Rukwa – North Malawi Rift Segment (this study).

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1637 Fig. 18. Examples of system-scale rift bifurcation in the (A) East African Rift System, (B) Red  
 1638 Sea Rift and (C) South Atlantic Rift; and examples of basin-scale rift bifurcation in the (D) Rukwa  
 1639 Rift (see Fig. 18A for location), (E) southern Malawi Rift and (F) Albertine Rift (see Fig. 18A for  
 1640 location). These examples show that the 2<sup>nd</sup> order bifurcations are integral components of inter-  
 1641 rift transfer zones where the coupling of rift segments take place.