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30 **CONTROLS OF BASEMENT FABRIC ON RIFT COUPLING AND DEVELOPMENT**
31 **OF NORMAL FAULT GEOMETRIES: INSIGHTS FROM THE RUKWA – NORTH**
32 **MALAWI RIFT**
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73 **Highlights**

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

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80

81 **ABSTRACT**

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

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

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119 1. INTRODUCTION

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

136 However, the relationship between rift segments along the western branch of the EARS
137 and the Precambrian shear zones is rather complex and warrants detailed and careful
138 examination. For example, the Precambrian NW-trending Aswa shear zone resulted in the
139 termination (rather than facilitation) of the northeastward propagation of the Albertine-Rhino
140 graben which represents the northern-most segment of the Western Branch (Katumwehe et al.,
141 2015) (Fig. 1A). On a basin scale, previous studies have also shown that pre-existing basement

142 shear zones can influence the localization of fault development (e.g., Phillips et al., 2016;
143 Kolawole et al., 2018), and in fact control fault segmentation and across-basin strain transfer at
144 later stages of rift development (e.g., Muirhead and Kattenhorn, 2018).

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

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

165 **2. GEOLOGIC SETTING**

166 *2.1. The Precambrian Domains*

167 The Rukwa-North Malawi Rift Segment is located within the NW-trending Paleoproterozoic
168 Ubendian orogenic belt which is sandwiched between the Archean Tanzanian craton in the
169 northeast and the Bangweulu cratonic block to the southwest (Figs. 2A-B; Fritz et al., 2013). The
170 Ubendian Belt is composed of different Precambrian terranes bounded by steep shear zones
171 (Delvaux et al., 2012). These terranes contain granulite-facies metamorphic rocks (2100-2025
172 Ma), amphibolite-facies metamorphic rocks and granitoids (1960-1800 Ma) that have undergone
173 dextral strike-slip shearing and granitic plutons (1090-1120 Ma), (Fritz et al., 2013). The
174 Paleoproterozoic Usagaran orogenic belt that extends NE-SW perpendicular to the Ubendian
175 orogenic belt in southern Tanzania, is composed of eclogites (~2000 Ma), volcano-sedimentary
176 cover with some low-grade metamorphism (~1920 Ma), and granitoids and granitoid gneisses
177 (1900-1730 Ma) (Fritz et al., 2013). The Usagaran and Ubendian orogenic belts resulted from
178 collision with the Tanzania craton, where the Usagaran orogenic belt was thrust onto the craton
179 and the Ubendian orogenic belt was accreted along the craton's margin because of strike-slip
180 motion (Daly, 1988; Lenoir et al., 1994). The Ubendian Belt was reactivated several times, first
181 at ~1860 Ma as a shear zone, then again at ~800 Ma and was subsequently reactivated about
182 every 200 Ma (Lenoir et al., 1994). Mapped shear zones along the Ubendian Belt include the
183 ~600 km long and >15 km-wide Mughese Shear Zone, the Mtose Shear Zone, and the Chisi
184 Shear Zone (Fig. 2; Daly, 1988; Schenk et al., 2006; Delvaux et al., 2012). Recent studies have
185 highlighted the role of the Mughese Shear Zone in fault development and the distribution of
186 seismicity in Northern Malawi Rift Basin (Dawson et al. 2017; Kolawole et al., 2018).

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188 2.2. *The Rukwa Rift, Northern Malawi Rift, and the Mbozi Block accommodation zone (RNMRS)*
189 The RNMRS evolved during the Permo-Triassic episode of rifting that affected southern and
190 eastern Africa, also known as Karoo rifting (Chorowicz, 2005). Outcrops of Karoo sediments
191 have been mapped along the southern end of the Rukwa Rift (Figure 2) and the northern section
192 of the North Malawi Rift Basin (Kilembe and Rosendahl, 1992). These sediments lie
193 unconformably over the Precambrian basement and consist mainly of sandstone, shale, and coal
194 and thicken towards the border faults providing evidence for reactivation of synthetic faulting in
195 the Permo-Triassic (Morley, 1992; Delvaux et al., 1992).

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

211 Malawi Rift (also known as the North Basin) which represents the southeastern end of the
212 RNMRS and it consists of a half-graben, bounded to the northeast by the Livingstone Fault (Fig.
213 1B). The Mbozi Block is referred to as an accommodation zone because it is thought to
214 accommodate and transfer relative strain between the Rukwa and North Malawi Rift Basins
215 (Delvaux and Hanon, 1993)

216 The Mbozi is a mass of Precambrian basement that is composed of Meta-basites and
217 intermediate granulites and quartzites of the Mbozi Terrane (Daly, 1988) and is bounded to the
218 southwestern by the Mughese Shear Zone (Fig. 2B), and overlain on the northeast by the
219 volcanic deposits of the Rungwe Volcanic Province (RVP). The RVP is a ~1500 km² area of
220 volcanic rocks and structures that evolved ca. 9 Ma (e.g., Fontijn et al., 2012), and a strong
221 tectonic control on the localization of volcanic centers have been inferred (e.g., Fontijn et al.,
222 2010, 2012). To the northeast of the RVP, a poorly defined NE-trending rift basin occurs, known
223 as the “Usangu Basin”, where Permo-Triassic to Recent sedimentary rocks overlie the
224 Precambrian basement (Mbede, 2002).

225 The crustal thickness beneath the Rukwa Rift is ~37.5 km (Kim et al., 2009), but varies
226 between ~33 km and ~39 km along the rift shoulder (Ufipa Plateau) (Hodgson et al., 2017), and
227 increases slightly to 41.1–42.1 km in the northwestern-most part of the rift where the rifting is
228 minimal. These suggest that overall, the crustal thinning beneath the rift has been minimal but
229 may be slightly more beneath the Songwe Trough (Njinju et al., 2018). Camelbeeck and Iranga
230 (1996) estimated ~42 km crustal thickness beneath the Songwe Trough. Whereas, an average
231 crustal thickness of 39 km has been estimated for the Rungwe Volcanic Province, ~37-39 km for
232 the North Malawi Rift, and 38-42 km for the Proterozoic terrains surrounding the North Malawi
233 Rift (Borrego et al., 2016; Njinju et al., 2018).

234 *2.3. Kinematics of the RNMRS*

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

257 3.2. Aeromagnetic Data

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

273 The vertical derivative edge filter has been very effective in the mapping of plan-view
274 trace of buried active faults from aeromagnetic data in different parts of the EARS (Kinabo et al.,
275 2007, 2008; Kolawole et al., 2017, 2018). Excluding the Rungwe Volcanic Province (RVP;
276 Figure 3) where volcanic materials overlie the crystalline basement, there is no information on
277 the presence of basaltic rocks along the fault segments interpreted in this study. Therefore, we
278 assume induced magnetization as the primary source of magnetization, except in the Rungwe
279 Volcanic Province (RVP) where volcanic deposits are present. However, we do not have

280 information on remanent magnetization in the RVP at this time. Due to the higher spatial
281 resolution of the Malawi aeromagnetic data (62 m grid cell size) compared to those covering
282 Zambia (225 m grid cell size) and Tanzania (250 m grid cell size), the magnetic anomalies are
283 most significantly better resolved in the Malawi part of the filtered aeromagnetic maps.

284

285 **4.0 RESULTS**

286 *4.1. Variation in rift morphology from topographic profiles*

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

296 Profile 1 (Fig. 3), obtained at the northern tip of the Rukwa Rift shows no pronounced
297 fault scarps, and the slight topographic high between Lake Tanganyika and Ufipa Fault
298 represents the northernmost tip of the Ufipa Plateau. In Profile 2, the surface morphology of the
299 rift shows sharp topographic gradients bounding the Rukwa Rift Valley. These topographic
300 gradients correspond to the scarps of the Ufipa Fault (600 m) and the Lupa Fault (750 m). In this
301 northern part of the Rukwa Rift, the Ufipa and Lupa Faults have comparable scarp heights, thus
302 illustrating a typical graben structure. In Profile 3, the rift structure changes into a half-graben

303 surface morphology with the Ufipa Fault having a significantly higher escarpment than the Lupa
304 Fault (~900 m difference). Profiles 4 to 7 show the same half-graben morphology for the Rukwa
305 Rift as in Profile 3; however, we observe that the Ufipa Fault scarp is much higher than the
306 topography of the Ufipa Plateau to its west along Profile 4.

307 Along Profiles 6 and 7, we observe that the Ufipa Fault scarp is lower than in the
308 northern profiles (Profiles 1-5) and that the Lupa Fault scarp is also higher than in the northern
309 profiles. In Profile 7, the Rukwa Rift splits into two basins separated by the Mbozi Block such
310 that the west basin (Musangano Trough) is bound by the Ufipa Fault to the southwest, and the
311 east basin (Songwe Trough) is bound by the Lupa Fault to the northeast. Profiles 7 to 9 shows a
312 continuous southeastward decrease in the scarp heights of the Ufipa and Lupa Faults; and
313 although the Ufipa Fault scarp is still visible south of the Mbozi Block along Profile 9, the Lupa
314 Fault scarp is significantly diminished. Profile 9 shows a gentle topographic transition from the
315 Musangano Trough to the Mbozi Block, but to the northeast of the Mbozi Block, the topography
316 spikes abruptly, representing the northern limits of the Rungwe Volcanic Province (RVP). In
317 Profile 10, the Ufipa Fault bounds what appears to be the southernmost extent of the Musangano
318 Trough, while the uplifted Mbozi – RVP domain dominates the terrain and drops off into the
319 Usangu Trough to the northeast. Profile 11 transects the northernmost tip of the North Malawi
320 Rift, where the RVP (bounded to the northeast by the Livingstone Fault scarp) represents the
321 most dominant structure in the terrain and the entire topography of the Mbozi Block and areas to
322 its southwest are 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.
333 Although the Malawi part of the merged data has the highest resolution, the moderate resolution
334 of the Tanzania and Zambia parts of the data allows for considerable delineation of the trends of
335 magnetic anomalies. Overall, the areas of basement exposures exhibit high amplitude, high
336 frequency and short wavelength magnetic anomalies that delineate lineaments of interpretable
337 trends (e.g., Kolawole et al., 2018). The high frequency lineaments can be easily observed on the
338 rift shoulders of the Rukwa and North Malawi Rifts (Fig. 4B), and are commonly truncated at the
339 rift margins by the rift-bounding faults (black arrows in Fig. 4B).

340 Within the rift valleys where sedimentary rocks overlie the deeply-buried basement
341 rocks, the detailed magnetic fabric of the basement becomes suppressed such that gradients in
342 the 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
345 basins are dominated by relatively lower amplitude, longer wavelength and lower frequency
346 anomalies.

347

348

349 4.3. SRTM DEM Fault trends and Aeromagnetic lineaments

350 We compare the along-axis geometry of the rift-bounding faults (from SRTM DEM) with the
351 metamorphic fabric (in plan view) of the host basement rocks along the rift shoulders (from
352 filtered aeromagnetic data) (Figs. 5-11). Figures 5-9 focus on the southwestern boundary of the
353 RNMRS, consisting of the Ufipa Fault of the Rukwa Rift, the southwestern boundary of the
354 Mbozi Block and the southwestern boundary faults of the North Malawi Rift. Whereas, Figures
355 10 and 11 focus on the northeastern boundary of the RNMRS, consisting of the Lupa Fault of
356 Rukwa Rift, the northeastern boundary of the Mbozi Block (i.e. the Rungwe Volcanic Province)
357 and the Livingstone Fault of the North Malawi Rift. We constrain our identification of the
358 Precambrian terranes and strike of their fabrics with previous field studies of the Precambrian
359 basement along the RNMRS (e.g., Daly, 1988; Wheeler and Karson, 1989; Lenoir et al., 1994;
360 Theunissen et al., 1996; Boven et al., 1999; Fernandez-Alonso et al., 2001; Ring et al., 2002;
361 Schenk et al., 2006; Delvaux et al., 2012, Lawley et al., 2013; Kolawole et al., 2018). Overall,
362 within the study area, we observe that the basement fabrics exhibit two styles, (1) discrete fabrics
363 which include isolated magnetic lineaments of strong amplitude; and (2) distributed fabrics
364 which encompass fabric sets of multiple medium-to-low amplitude magnetic lineaments as
365 distributed fabrics.

366

367 4.3.1. Southwestern boundary of the RNMRS

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

372 WNW-ESE Chisi Fault at a high angle (Fig. 5A). The Chisi Fault aligns with a strong WNW-
373 ESE magnetic-high lineament (discrete fabric) (Fig. 5B-C) known as the Chisi Shear Zone,
374 which extends eastward into the rift basin (Theunissen et al., 1996; Boven et al., 1999; Schenk et
375 al., 2006; Fig. 2B). Also, the truncated Ufipa Fault segment aligns with the Ufipa Terrane
376 basement fabrics (distributed fabrics). The North Ufipa Fault and Chisi Fault link at a very high
377 angle to form a salient that point basinward (the Chisi Salient).

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

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

395 metamorphic fabrics that strike WNW-ESE to NW-SE, oblique to the fault but in which subtle
396 bends in the fault trend align with the basement fabric.

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

414 Detailed analyses of the onshore faults along the hinge zone of the Northern Malawi Rift
415 (Karonga area) are well documented in Kolawole et al. (2018). Major onshore hinge zone faults
416 include the Karonga Fault (KF), St. Mary Fault (SMF), Kaporo Fault (KPF), Lupaso Fault (LF),
417 Katesula Fault (KTF) and the Mbiri Fault (Figs. 9A-C). Although the Karonga Fault cuts the

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

426

427 *4.3.2. Northeastern boundary of the RNMRS*

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

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

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

448

449 **5.0 DISCUSSION**

450 *5.1. Rift architecture*

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

463 The significantly lower scarp-height of the Lupa Fault suggests either that it has not been
464 very active in Cenozoic times or that it has been heavily eroded since the cessation of Mesozoic
465 rifting. However, based on these observations, we interpret that in the earlier rifting episodes
466 (especially in the Permo-Triassic Karoo episode), the Lupa Fault played the role of the major
467 border fault such that the basin defines a typical half-graben geometry; but in the present
468 Cenozoic phase of rifting, the Ufipa Fault appear to have been preferentially accommodating
469 more strain. Therefore, we suggest that the Rukwa Rift is possibly transitioning into an
470 asymmetric-graben geometry. An asymmetric-graben is a graben with EMVD greater on one
471 border fault compared to the other one, such that the basin polarity has shifted to the fault with
472 the greater 'exposed minimum vertical displacement' (EMVD) (Lao-Davila et al., 2015). The
473 implications of the present Rukwa Rift morphology on the Lupa Fault may reflect temporal and
474 spatial migration of strain accommodation from a previously dominant border fault into another
475 one that has been previously less-dominant. This could possibly be explained by the Scholz and
476 Contreras (1998) suggestion that when a rift-bounding fault attains some limiting offset, motion
477 on the fault will cease, and strain will be transferred to a new fault.

478

479 *5.2. The Southwestern Boundary of the RNMRS and relationships with Precambrian Basement*

480 *Fabric*

481 In the Chisi area, the Northern Ufipa Fault segment terminates against the Chisi Shear Zone
482 along which the Chisi Fault segment developed. The termination of the Ufipa Fault at its
483 intersection with this shear zone exemplifies one of the roles of pre-existing basement structures
484 as temporal and/or spatial mechanical 'barriers' that arrest and delimit the continuous lateral
485 propagation of a fault. Several studies on fracture propagation have demonstrated that fractures

486 are principally bifurcated, blunted, and/or arrested when they intersect discontinuities, stress
487 barriers and/or rock layers of significantly-contrasting mechanical properties along their path of
488 propagation (e.g., Helgeson and Aydin, 1991; Gudmundsson and Brenner, 2001; Zhang et al.,
489 2007; Zhang and Jeffrey, 2008). Other examples of normal fault termination at long-lived
490 basement shear zones include the case of the Albertine-Rhino Graben terminating at the Aswa
491 Shear Zone (Katumwehe et al., 2015) and the Okavango Rift border faults against the Sekaka
492 Shear Zone (Modisi et al., 2000). We suggest that both the reactivation of the Chisi Shear Zone
493 into the Chisi Fault and termination of fault segments at the shear zone demonstrate the strong
494 influence of the Chisi Shear Zone on the development of this part of the Rukwa Rift.

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

506 The Tunduma-Kaseye area of Malawi, through the Misuku Mountains (Fig. 8A)
507 constitute the southern boundary of the Mbozi Block. Although, the SRTM DEM shows that the
508 sub-aerial expression of the Ufipa Fault dies out roughly mid-way between Tunduma and

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

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

531 fact suggest the possible influence of pre-existing basement fabric on the stepping geometries of
532 dike intrusions during their emplacement in host metamorphic rocks (Fig. 13B).

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

554 Based on the lateral dike separation across the fault on our aeromagnetic data, we estimate a
555 minimum of 500 m lateral displacement along the Mughese Fault (Fig. 13C). It is also possible
556 that this estimated offset only represents the lateral component of an oblique-normal slip along
557 the fault. In Figure 14, we present a conceptual model that summarizes our interpretation of the
558 Chitipa Dike geometry and the interaction of the Mughese Fault with the dike.

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

567 Along the southwest margin of the North Malawi Rift (Karonga area), the Mughese Fault
568 diffuses into a zone of wide-spread faulting where the southeast-ward bend of the Mughese
569 Shear Zone controls the development of the normal faults and recent seismicity along the basin
570 hinge margin (Fig. 9A-C) (Kolawole et al., 2018; Dawson et al., 2018). Further south of Karonga
571 town, the NNW-striking Mbiri Fault is the dominant fault structure in terms of its length (and
572 displacement?) along this part of the hinge zone of the North Malawi Rift. We do not observe
573 any direct spatial connectivity between the Mughese Fault and the Mbiri Fault. However, based
574 on the sub-parallel geometry of both faults and the structural dominance of the Mbiri Fault in the
575 area, we suggest that the Mbiri Fault could possibly represent a continuation of the Mughese
576 Fault into the hinge zone of the Malawi Rift North Basin. It is also important to note that the

577 Mbiri Fault is synthetic to the Livingstone border Fault. Following the observations and
578 interpretations above, we suggest that there exists a well-developed continuous connectivity of
579 rift-related structures along the southwestern boundary of the RNMRS, facilitated by the extent
580 of the Mughese Shear Zone and the Ufipa Terrane. Interestingly, the linking of the oppositely-
581 dipping Ufipa and Mbiri Faults by the Mughese strike-slip fault describes a structure that,
582 overall, is similar to that of the Morley et al. (1990) convergent-approaching normal fault
583 system.

584

585 *5.3. The Northeastern Boundary of the RNMRS and relationships with Precambrian Basement* 586 *Fabric*

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

594 The southern segment of the Lupa Fault transitions into the Rungwe Volcanic Province
595 (RVP) where surficial cover of volcanic deposits obscures the southward continuation of the
596 Lupa Fault (Fig. 11A). In addition, the presence of mafic volcanic deposits in the RVP (e.g.,
597 Fontijn et al., 2012) makes it difficult to make a reliable interpretation of the magnetic fabric of
598 the underlying Precambrian basement (Fig. 11B). However, we find that a distinct magnetic-high
599 lineament aligns with the Mbaka Fault surface trace (white arrows in Figs. 11A and 11B). Also,

600 the distribution of volcanic centers in the RVP show alignment with both the Mbaka Fault trace
601 and a subtle curvilinear gradient (black arrows in Fig. 11B). Further south, the curvilinear
602 gradient connects with the Livingstone Fault, the northeastern border fault of the North Malawi
603 Rift. This curvilinear gradient coincides with the location and extents of the so-called “Ngozi-
604 Rungwe Line” of Fontijn et al. (2010), described as a buried fault system that served as a conduit
605 for magmatic fluids to migrate to the surface volcanic vents. Therefore, although it is possible
606 that the magnetic anomalies in this area are affected by remanent magnetization from the
607 volcanic deposits, we interpret that this aeromagnetic gradient provides a possible subsurface
608 evidence of the fault system (Ngozi-Rungwe Line) that connects the Lupa Fault and the
609 Livingstone Fault across the RVP. The filtered aeromagnetic data and previous field studies
610 (e.g., Wheeler and Karson, 1989) shows that the Livingstone Fault segments align with and
611 reactivated the fabric of the Upangwa Terrane (Figs. 11B-C). The observations and
612 interpretations above suggest that there exists a well-developed continuous connectivity of rift-
613 related structures along the northeastern boundary of the RNMRS. However, the relationship
614 between the basement fabric and the buried faults beneath the volcanic deposits remains unclear.

615

616 *5.4. Implications for Rift Development*

617 *5.4.1. Rift Coupling*

618 In the Rukwa Rift, the substantial dominance of the Ufipa Fault rift shoulder over that of the
619 Lupa Fault may imply that the Ufipa Fault is the present-day active border fault of the Rukwa
620 Rift. This proposition may be supported by the hypocentral location of the 1994 Mw5.9 Rukwa
621 earthquake and its aftershocks with epicentral location in the northern part of the rift (Fig. 12;
622 Zhao et al., 1997). The nodal planes of the earthquake focal mechanism solution are broadly

623 consistent with the orientation of both the Lupa and Ufipa faults, and relative position of
624 aftershocks to the main shock is well determined (Fig. 12; Zhao et al., 1997). Considering the
625 uncertainty range of the earthquakes, the spatial distribution of the aftershocks relative to the
626 main shock delineates a sub-horizontal fault zone that most fits the subsurface projection of the
627 Ufipa Fault (Fig. 12). In addition, field investigations of the Kwera relay ramp (see Fig. 6 for
628 location) revealed features that indicate recent activity along the Ufipa Fault (Delvaux et al.,
629 2012). Camelbeeck and Iranga (1996) observed several lower crustal seismicity in the Rukwa
630 Rift with most of the events clustering beneath the Songwe Trough and the Rungwe Volcanic
631 Province (southern parts of the rift; Fig. 1B). The locations of the clusters suggest activity along
632 the southern Lupa Fault and Mbeya Range Fault. However, since the scarp height (and throw?)
633 of the Ufipa Fault decreases southwards (Fig. 3), and the throw on the Lupa Fault increases
634 southwards (and rapidly along the Songwe Trough) (Morley et al., 1992), we infer that the
635 present border fault role of the Ufipa Fault excludes the southernmost parts of the Rukwa Rift.

636 It has also been observed that the early stage of continental rifting is typically
637 characterized by the development of along-axis alternating polarity of rift segments, rift border
638 faults, uplifted rift flanks (e.g., Bosworth, 1985; Rosendahl, 1987; Hayward and Ebinger, 1996;
639 Lao-Davila et al., 2015). The zones of polarity changes (transfer/accommodation zones) serve to
640 transfer extensional strain between the rift segments and link the border faults which often have
641 variable structural styles and geometries (e.g., Morley et al., 1990; Wilson, 1999). Within young
642 continental rift settings, interactions between these large border faults lead to the systematic
643 coupling of border faults and rift segments across the transfer zones, and subsequent growth of
644 the rift system (e.g., Corti, 2012). Along the RNMRS, the alternating location of the of rift
645 shoulder uplift (SW in Rukwa Rift and NE in North Malawi Rift), typical of coupled rift

646 segments, suggest that the RNMRS can be considered a coupled rift segment. Further, our study
647 here shows that there is in fact, continuous structural continuation along the northeastern and
648 southwestern margins of the RNMRS, typical of a coupled rift segment. Although, studies in the
649 EARS and illustrations of its rift segments had always assumed this to be true, we hereby
650 provide evidence supporting it, for the first time. In the West Antarctic rift system, the
651 localization of recent volcanism along transverse structures within an accommodation zone (the
652 Discovery accommodation zone) suggests active structural interactions between the flanking rift
653 segments (Wilson, 1999). Therefore, we further suggest that the focusing of Neogene volcanism
654 (e.g., Fontijn et al., 2010, 2012) along the northeastern boundary faults of the Mbozi
655 accommodation zone (Fig. 15A) may be indicative of the ongoing coupling of the Rukwa and
656 North Malawi Rift's northeastern border faults.

657

658 *5.4.2. Rift Kinematics*

659 Several studies have suggested that the development of the RNMRS has been dominated by
660 dextral strike-slip kinematics (e.g., Chorowicz, 1989; Daly et al., 1989; Wheeler and Karson,
661 1994; Kervyn et al., 2006; Mortimer et al., 2007). However, analyses of fault architecture, fault-
662 kinematics, paleostress and present-day earthquake focal mechanism solution in the Rukwa Rift
663 show that the present-architecture of the rift largely developed within a pure extensional setting
664 with extension direction orthogonal to the trend of the RNMRS (Morley, 2010; Delvaux et al.,
665 2012). Furthermore, Delvaux et al. (2012) observed dextral strike-slip faulting along the fault
666 systems bounding the Rukwa Rift, but concluded that the strike-slip event was transitory and was
667 associated with an early Mesozoic transpressional event that resulted in the inversion of Karoo
668 sediments. In this study, we observe the existence of a well-defined strike-slip fault bounding the

669 SW margin of the Mbozi Block that reactivated the Precambrian Mughese Shear Zone. We also
670 observe lack of present-day activity along the strike-slip fault, and that this fault displaced a
671 buried mafic dike with at least 500 m of dextral offset.

672 In the absence of chronological data on the mapped dike, we posit that the dike is most-
673 likely associated with the widespread late-Karoo dike swarms observed in the Luangwa Rift and
674 Shire Graben (southern Malawi) (Castaing, 1991; Van de Velde and De Waele, 1998). We refer
675 to this strike-slip fault as the “Mughese Fault”, and the buried dike as the “Chitipa Dike”. The
676 Chitipa Dike, presented for the first time in this work, may constitute the most excellent record
677 of strike-slip kinematics along the RNMRS. Although, our results agree with Delvaux et al.
678 (2012) in that the strike-slip faulting along the RNMRS was short-lived, we suggest that future
679 geochronological analyses of this intrusion may provide the most-reliable constraint on the
680 timing of strike-slip faulting event. It is also interesting to note that if the Mughese strike-slip
681 fault is post-Karoo, its development represents a late reactivation of the Mughese Shear Zone in
682 the evolution of the RNMRS. However, late reactivation of rift-oblique basement shear zones is
683 not uncommon in rift basins (e.g., Muirhead and Kattenhorn, 2018).

684 Following the considerations above, we present cartoons of the RNMRS, illustrating the
685 continuous structural connectivity along the northeast and southwest boundaries guided by the
686 basement fabrics (Fig. 15B), and possible subsurface geometries and interactions of the domain-
687 bounding structures (Fig. 15B-E). The inferred dominance of the Ufipa Fault in the northern and
688 central parts of the Rukwa Rift (Fig. 12) suggest possible truncation of the Lupa Fault at depth,
689 such that the load of the basin hanging wall block is being carried by the Ufipa Fault (Fig. 15B).
690 However, seismic data is needed to confirm this interpretation. We illustrate a possible spatial
691 relationship between the RVP magma pathways and the Mbozi Block bounding faults in Figure

692 15C. In Figure 15D-E, we show a generalized basin geometry and flip in border fault polarity
693 from the Malawi Rift North Basin to the Usisya Basin. Overall, we posit that, along the
694 northeastern boundary of the Mbozi Block transfer zone strain is accommodated by magmatism
695 utilizing pre-existing fault systems, whereas, along the southwestern boundary, strain is
696 accommodated by dextral strike-slip faulting.

697

698 *5.5. Control of basement fabrics on normal fault geometries*

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

713 Curvilinear normal faults have been observed at various scales and at different
714 extensional tectonic settings (Fossen and Rotevatn, 2016). However, the first order curvilinear

715 normal faults are typically characterized by segment boundaries with salients (cusps) that plunge
716 basin-ward e.g., Salt-lake salient and Transverse Mountain salients of the Wasatch Fault in Utah
717 (Fig. 16A), and the Gullfaks salient in the North Sea (Fig. 16B) (Fossen and Rotevatn, 2016).
718 Also, the reported curvilinear faults show characteristic basin-ward concave geometries.
719 However, the South Oquirrh Mountains normal fault zone, although curvilinear (Wu and Bruhn,
720 1994), exhibits striking basin-ward convex geometry in which the cusps point into the footwall
721 of the fault (Fig. 16A). Wu and Bruhn (1994) suggested that convex curvilinear geometry of the
722 South Oquirrh Mountains normal fault zone developed by sequential propagation of the fault into
723 its foot-wall, guided by linkage across smaller en-echelon faults created by the lateral shear
724 components at the tips of the propagating fault. Here, in the Rukwa Rift, we observe both
725 convex- and concave-curvilinear normal fault geometries along the Ufipa and Lupa Faults. The
726 central Ufipa Fault (Fig. 6) and southern Lupa Fault (Kapalala-Mwambani area in Fig. 10A-C)
727 exhibit convex-curvilinear normal fault geometries, whereas the northern Ufipa Fault and the
728 Chisi Fault demonstrate concave-curvilinear fault geometries (linked at the Chisi salient) (Fig.
729 5). Also, we find striking similarities between the concave- and convex-curvilinear fault
730 geometries of the Rukwa Rift (Fig. 16C) with those in the southern Malawi Rift (Fig. 16D), the
731 Jurassic sedimentary sequence of the northern North Sea rift (Gullfaks area) (Fig. 16B), and the
732 Provo-Salt Lake City area (Fig. 16A). As show in Figure 16D, the segments of the Bilila-
733 Mtakataka Fault in southern Malawi Rift present excellent examples of convex-curvilinear
734 normal fault geometries (Jackson and Blekinsop, 1997). Recent studies on the relationships
735 between the basement fabrics and the Bilila-Mtakataka Fault segments (Johnson et al., 2018;
736 Hodge et al., 2018) show that some of the segments appear to align with the distributed basement
737 fabrics, while others cut across the basement fabrics.

738 Based on the observations above, we present conceptual models for the control of
739 various configurations of pre-existing basement fabrics on the development of curvilinear normal
740 fault plan-view geometries (Fig. 17). We show how discrete and distributed basement fabrics and
741 combinations of the two categories of fabrics can influence the plan-view geometry of normal
742 faults. However, there is need to better understand (1) the influence of the basement fabrics on
743 the geometries of curvilinear normal faults in 3-dimensions, (2) the influence of the extension
744 direction on the development of the observed curvilinear normal faults in areas where the
745 basement fabric present mechanical anisotropy.

746 Although, Fossen and Rotevatn (2016) provide evidence of subsidiary short-cut faulting
747 across a salient, suggesting an impending evolution of concave-curvilinear faults into rectilinear
748 faults, it is not yet clear if the model applies to convex-curvilinear normal faults since the two
749 styles of faults are geometrically different. However, the synthetic Bilila-Mtakataka and the
750 Chirobwe-Ncheu Faults (Fig. 16D) in southern Malawi Rift may provide some insight. Since the
751 Chirobwe-Ncheu Fault is older than the Bilila-Mtakataka Fault (Jackson and Blekinsop, 1997),
752 the rectilinear geometry of the Chirobwe-Ncheu Fault suggests that the apices of convex
753 curvilinear segments may likewise eventually get breached to form more-rectilinear fault
754 segments. Conversely, we observe the opposite of this model along the Lupa Fault, where the
755 more-rectilinear northern Lupa Fault has accommodated much less strain compared to its
756 curvilinear southern segment which has the most strain within the Rukwa Rift (Morley et al.,
757 1992). Therefore, we suggest that although the model of temporal progression from a curvilinear
758 to rectilinear fault geometry may apply to some large normal faults, it may not apply to others.

759

760

761 5.6. Rift Bifurcation

762 The basin scale splaying of the Rukwa Rift around the Mbozi Block into the Musangano
763 and Songwe Troughs (Fig. 1B) obviously represents a smaller-scale of rift bifurcation when
764 compared to the continental scale bifurcation of rift systems around microplates. Examples of
765 such continental-scale rift bifurcation include the branching of the East African Rift around the
766 Tanzania microplate into the western and eastern branches (Fig. 1A; e.g., Rosendahl, B.R., 1987;
767 Versfelt and Rosendahl, 1989), the Red Sea Rift around the Sinai microplate into the Gulf of
768 Suez Rift and Dead Sea Transform, and the South Atlantic Rift around the Sergipe microplate
769 into the Tucano-Recôncavo Rift and Sergipe-Alagoas Transform (e.g., Szatmari and Milani,
770 1999) (Figs. 18A-C). Based on scale distinction, we therefore refer to the continental rift-system
771 scale bifurcation as first (1st) order rift bifurcation (Figs. 18A-C) and the rift-basin scale
772 bifurcation as second (2nd) order rift bifurcation (Fig. 18D-F). Similar to the Rukwa Rift, 2nd
773 order rift bifurcations are common along the East African Rift System. Examples include the
774 Southern Malawi Rift bifurcation around the Shire Horst, the Shire Graben bifurcation around
775 the Namalambo Horst, and the Albertine Graben bifurcation around the Rwenzori Block (Fig.
776 18B; e.g., Castaing, 1991; Koehn et al., 2008; Lao-Davila et al., 2015; Xue et al., 2017).

777 Regardless of scale, numerical models have showed that inherited structural
778 heterogeneity and lateral strength variations are key controls on rift bifurcation (e.g., Brune and
779 Autin, 2013; Brune et al., 2017). However, it appears that 1st order bifurcations commonly occur
780 at the tip of pre-existing microcratonic blocks along the path of propagation of a continental rift
781 system (e.g., Fig. 18A). Also, 2nd order bifurcations appear to occur at the transfer zones between
782 approaching rift segments, possibly due to a high tendency for the development of interfingering
783 fault blocks in the transfer zones between colinear approaching rift segments (Morley, 1995) and

784 lateral rotation of the trapped blocks in the transfer zones between overlapping approaching rift
785 segments (Koehn et al., 2008).

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

801

802 **6.0 CONCLUSIONS**

803 Our topographic analyses of the morphology of the RNMRs and detailed study of the
804 relationships between the pre-existing basement fabric and rift-related faults provide, for the first
805 time, evidence supporting the coupling of the Rukwa and North Malawi Rift. Our topographic
806 analyses in the Rukwa Rift suggest that the Ufipa Fault is the present-day active border fault of

807 the rift. We find that the Ufipa fault is the dominant topographic feature in the northern part of
808 the RNMRS and diminishes as it encounters the Mbozi block where it becomes a strike slip fault
809 (Mughese Fault), at which point the border fault polarity flips and the Livingstone Fault is the
810 dominant fault in the southern part of the RNMRS.

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

824 Furthermore, we show the influence of pre-existing basement fabrics on the development
825 of the RNMRS as evidenced in the geometry, termination and kinematics of the rift-bounding
826 fault segments. Our observations suggest that curvilinear normal fault geometries developed in
827 areas where the basement fabrics are either curvilinear, composed of superposed sets of
828 differently-orientated fabrics, or not favorably oriented to the extensional stress field. Whereas,
829 long, rectilinear fault geometries with narrow or almost unidentifiable breached-relay zones

830 developed in areas where the pre-existing basement fabrics are roughly rectilinear, suggesting
831 the greater likelihood of occurrence of tip-to-tip linkage of fault segments.

832 Finally, we present the existence of a buried Pre-Cenozoic strike-slip-faulted mafic dike,
833 which we suggest is potentially the most excellent record of strike-slip kinematics along the
834 RNMRS. We further suggest that future geochronological analyses of this intrusion may provide
835 the most-reliable constraint on the timing of the controversial strike-slip faulting event along the
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837

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847

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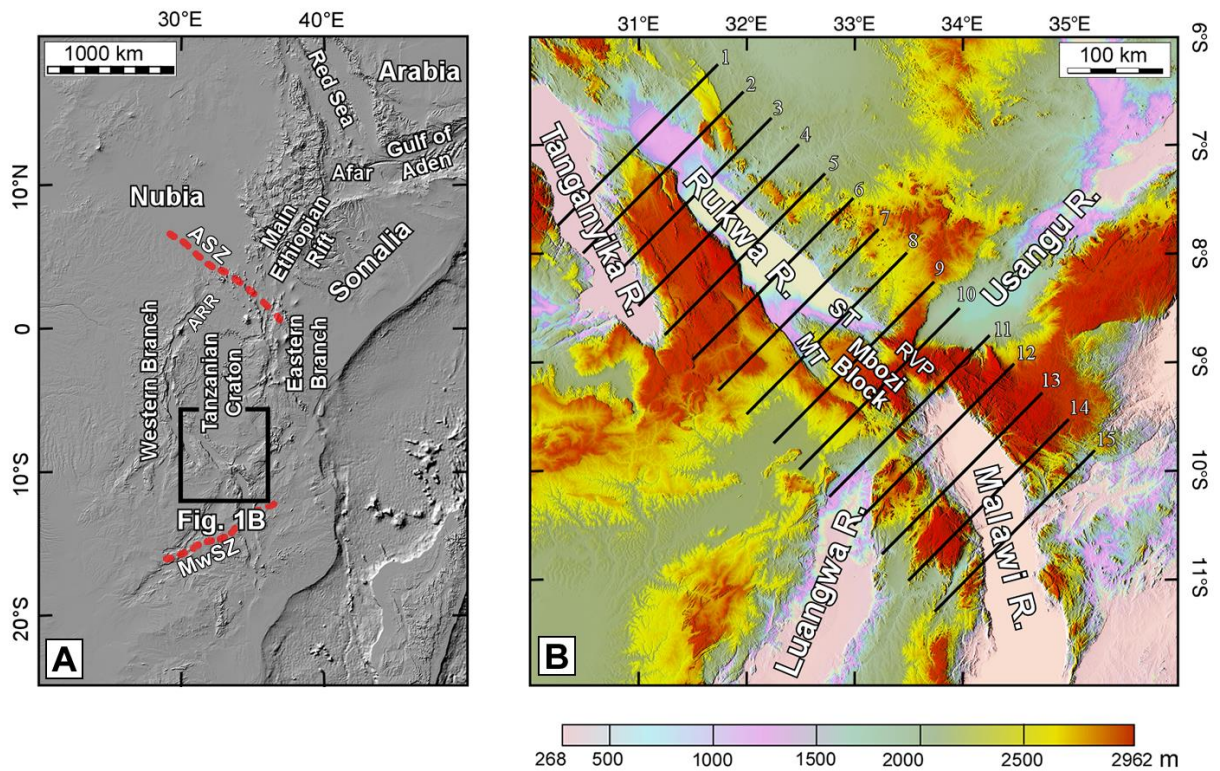


Fig.1. (A) Topographic map of the East African Rift System, showing the segments of the rift system and the location of the Rukwa-North Malawi Rift Segment (RNMR) (black square). (B) Digital Elevation Model (DEM) of the RNMR showing the different domains. Solid black lines represent topographic profile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

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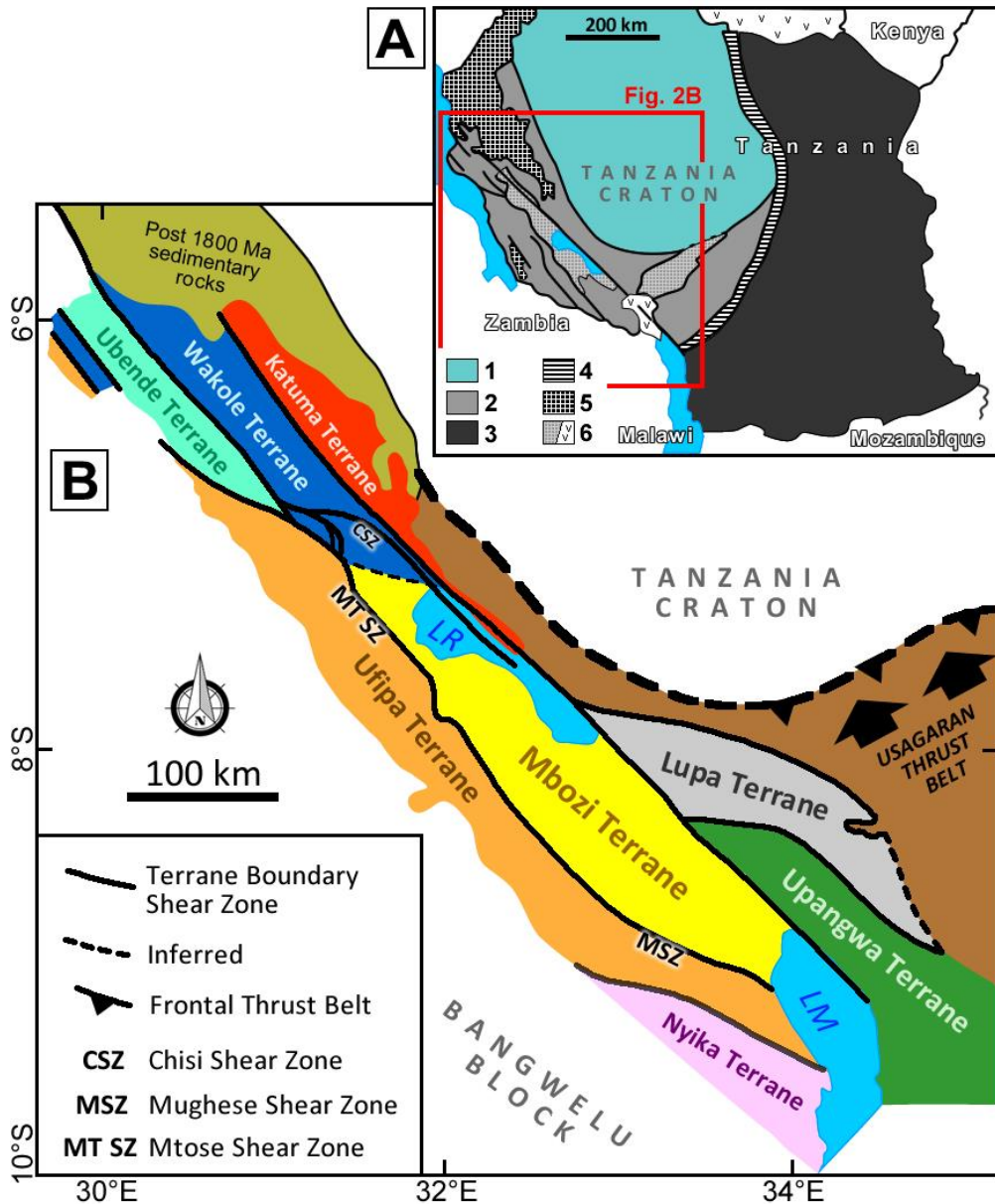
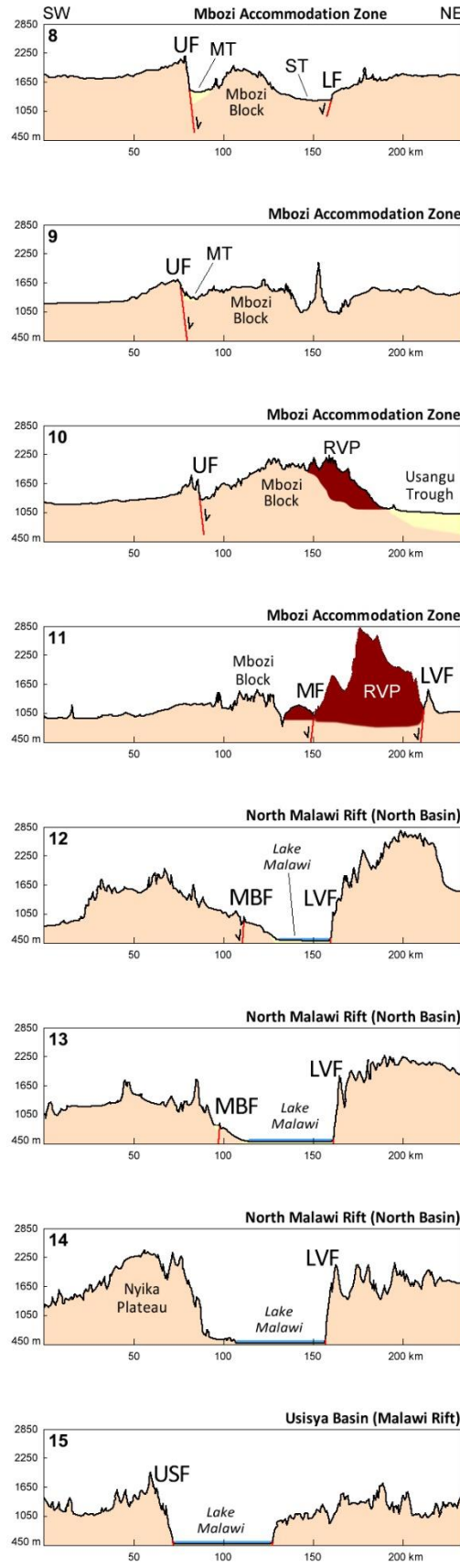
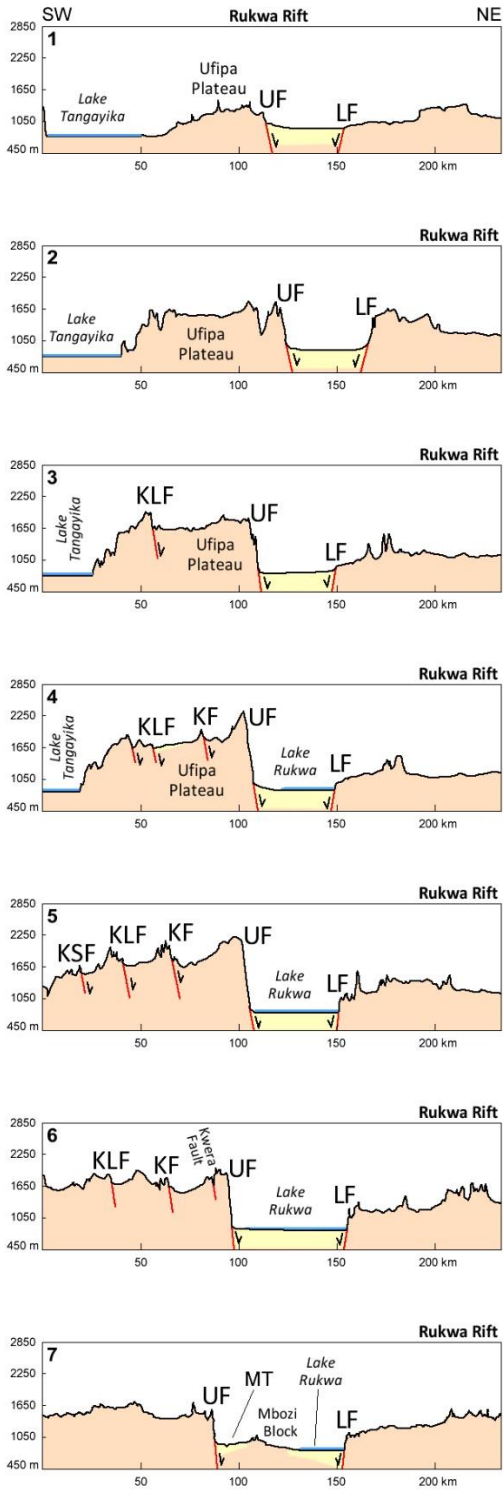


Fig. 2. (A) Precambrian domains around the Tanzanian Craton (modified after Theunissen et al., 1996; Boven et al., 1999; Fernandez-Alonso et al., 2001; Schenk et al., 2006). 1 = Archean craton; 2 = Paleoproterozoic Usagaran and Ubendian orogenic belts; 3 = Mozambique orogenic belt; 4 = western limit 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.

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— Normal Fault
 ■ Cenozoic Sediments
 ■ Rungwe Volcanics
 ■ Precambrian Basement

1177 Fig. 3. Topographic profiles across the Rukwa - North Malawi Rift segment. Profile
1178 numbers correspond to the profiles in Figure 1B. KLF = Kalambo Fault, KF = Kanda
1179 Fault, KSF = Kasanga Fault, LF = Lupa Fault, LVF = Livingstone Fault, MB = Mbozi
1180 Block, MBF = Mbiri Fault, MF = Mbaka Fault, MT = Musangano Trough, RVP =
1181 Rungwe Volcanic Province, ST = Songwe Trough, UF = Ufipa Fault, USF = Usisya
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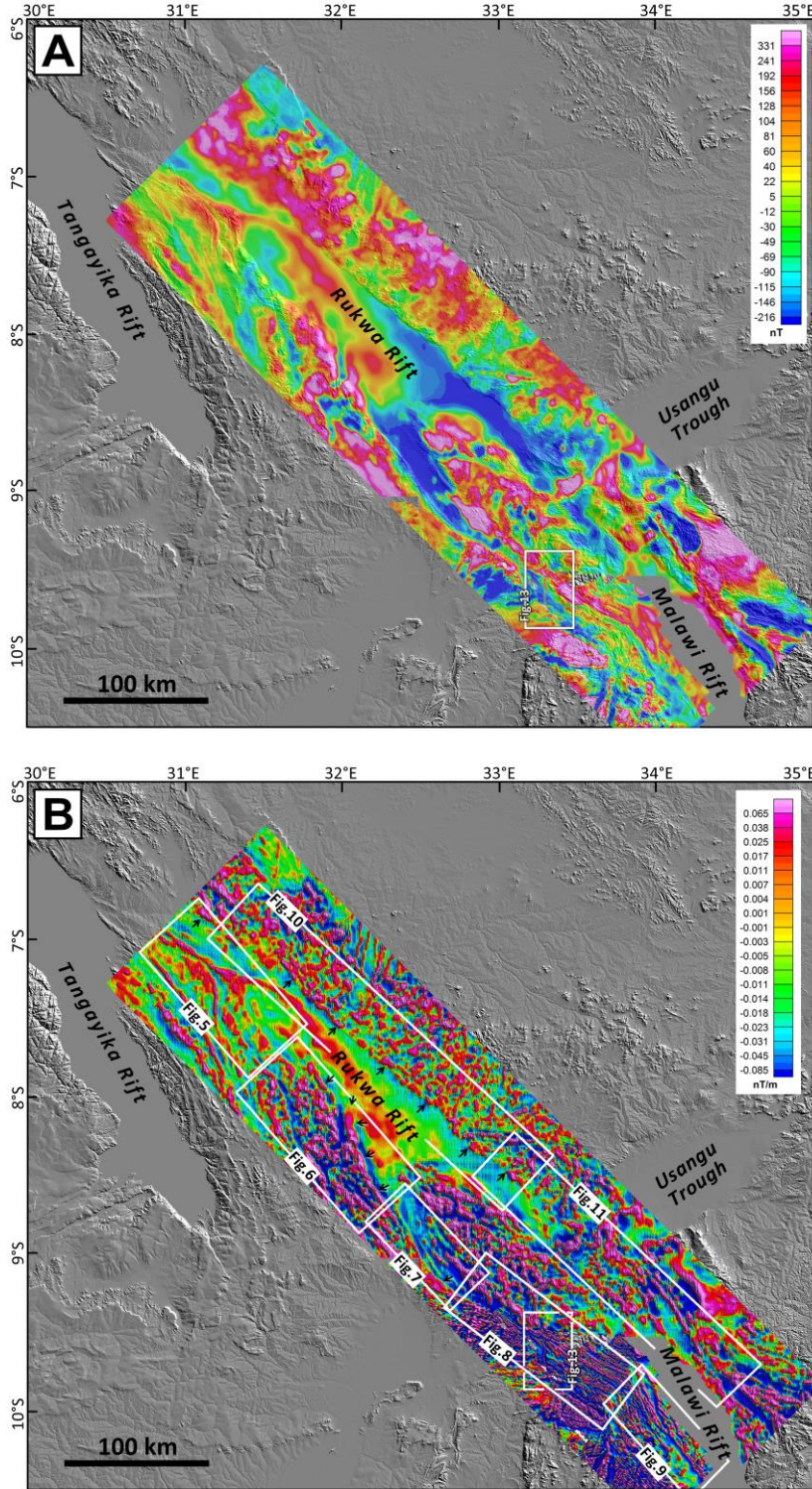


Fig. 4. (A) The reduced to pole Total Magnetic Intensity (RTP-TMI) map of the Rukwa-North Malawi Rift area, draped over the topographic digital elevation model of SW Tanzania. (B) The 1st vertical derivative map of the RTP-TMI map of the Rukwa-North Malawi Rift area draped over the topographic digital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

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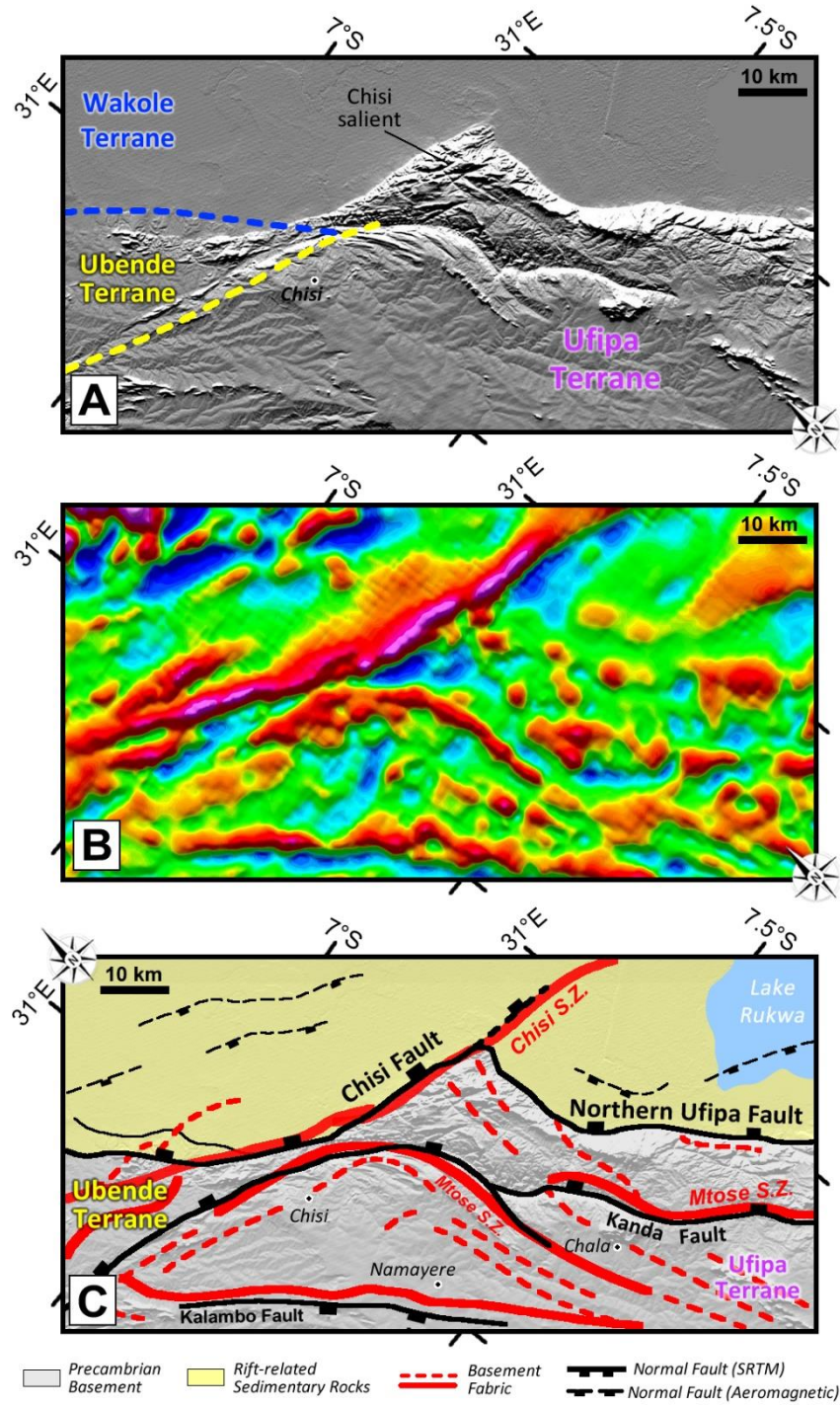


Fig. 5. Northernmost part of the Ufipa Fault, the SW boundary fault of the Rukwa Rift. Topographic digital elevation model in the top panel (A), the vertical derivative of the magnetic data in the middle panel (B), and a structural interpretation in the bottom panel (C).

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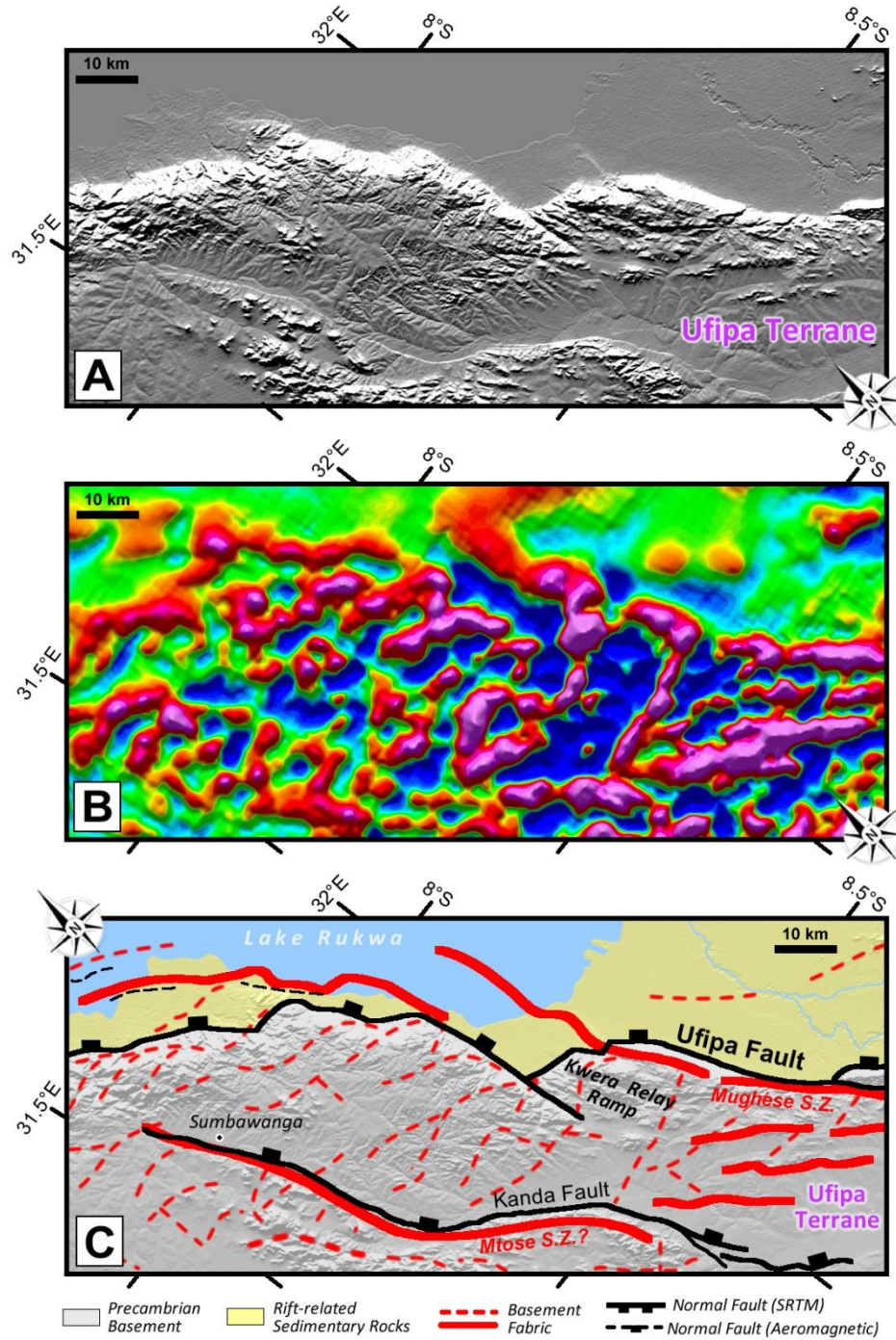


Fig. 6. Central segment of the Ufipa Fault, SW boundary of the Rukwa Rift. Topographic digital elevation model in the top panel (A), the vertical derivative of the magnetic data in the middle panel (B), and a structural interpretation in the bottom panel (C).

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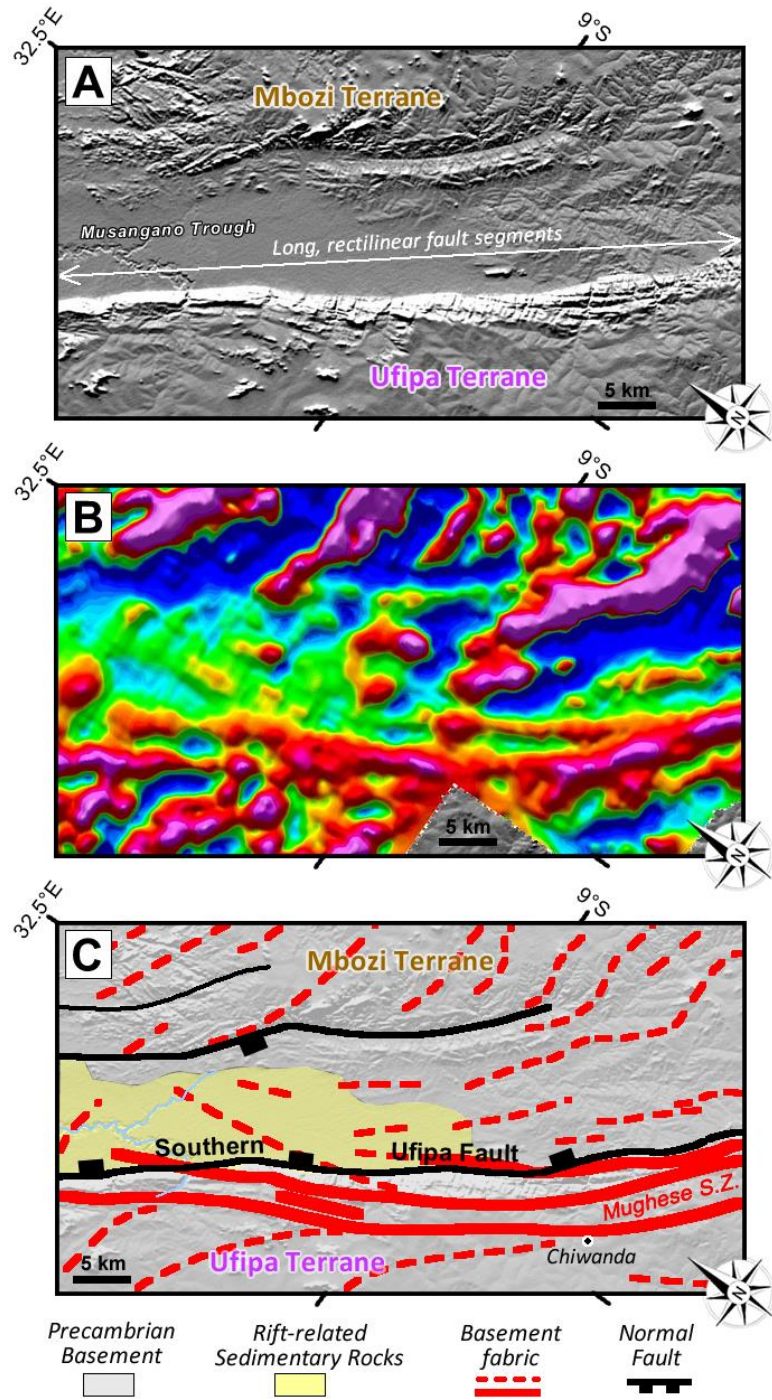


Fig. 7. The Musangano Trough part of the SW boundary of the Rukwa Rift. Topographic digital elevation model in the top panel (A), the vertical derivative of the magnetic data in the middle panel (B), and a structural interpretation in the bottom panel (C).

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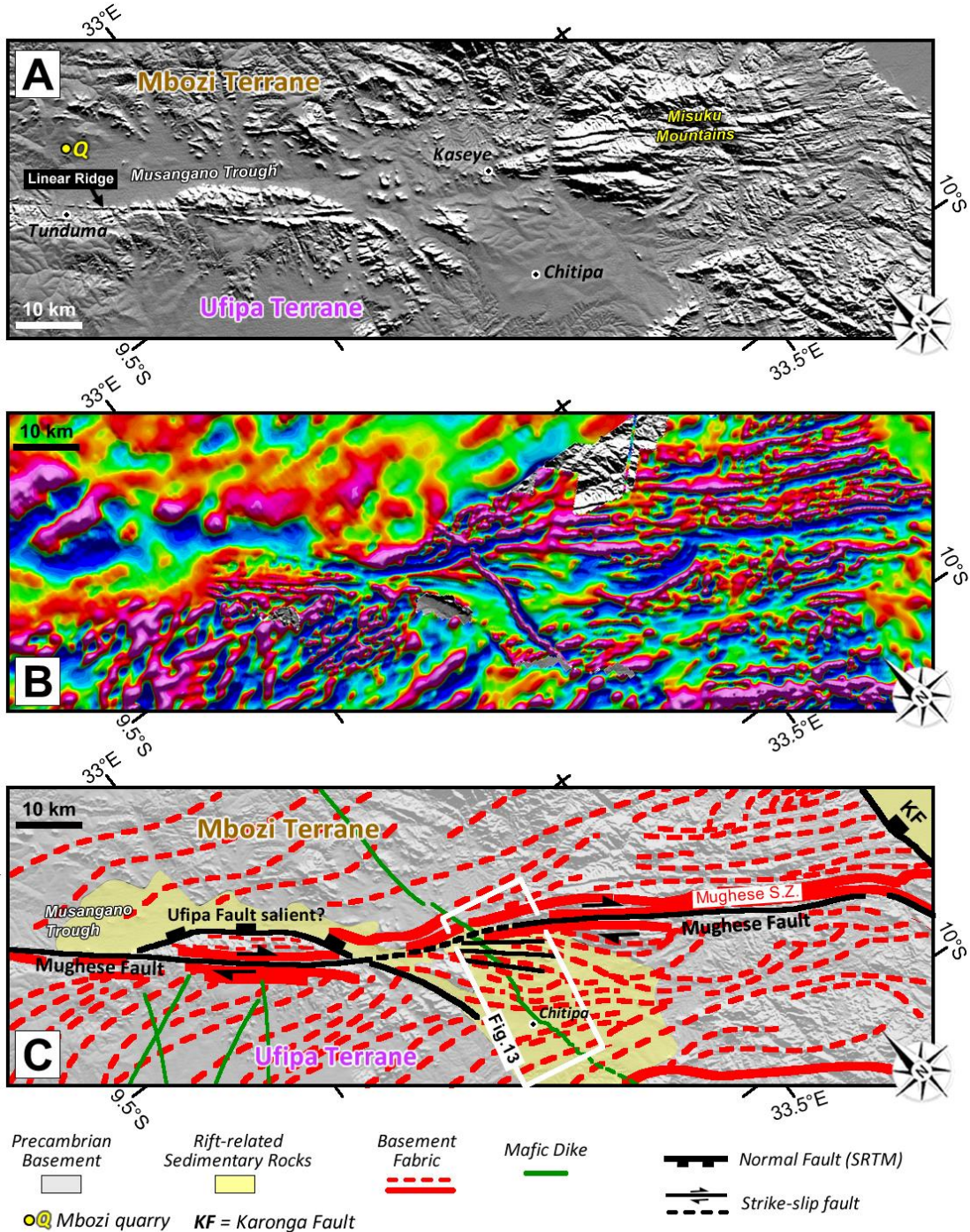


Fig. 8. The SW margin of the Mbozi Block. Topographic digital elevation model in the top panel (A), the vertical derivative of the magnetic data in the middle panel (B), and a structural interpretation in the bottom panel (C).

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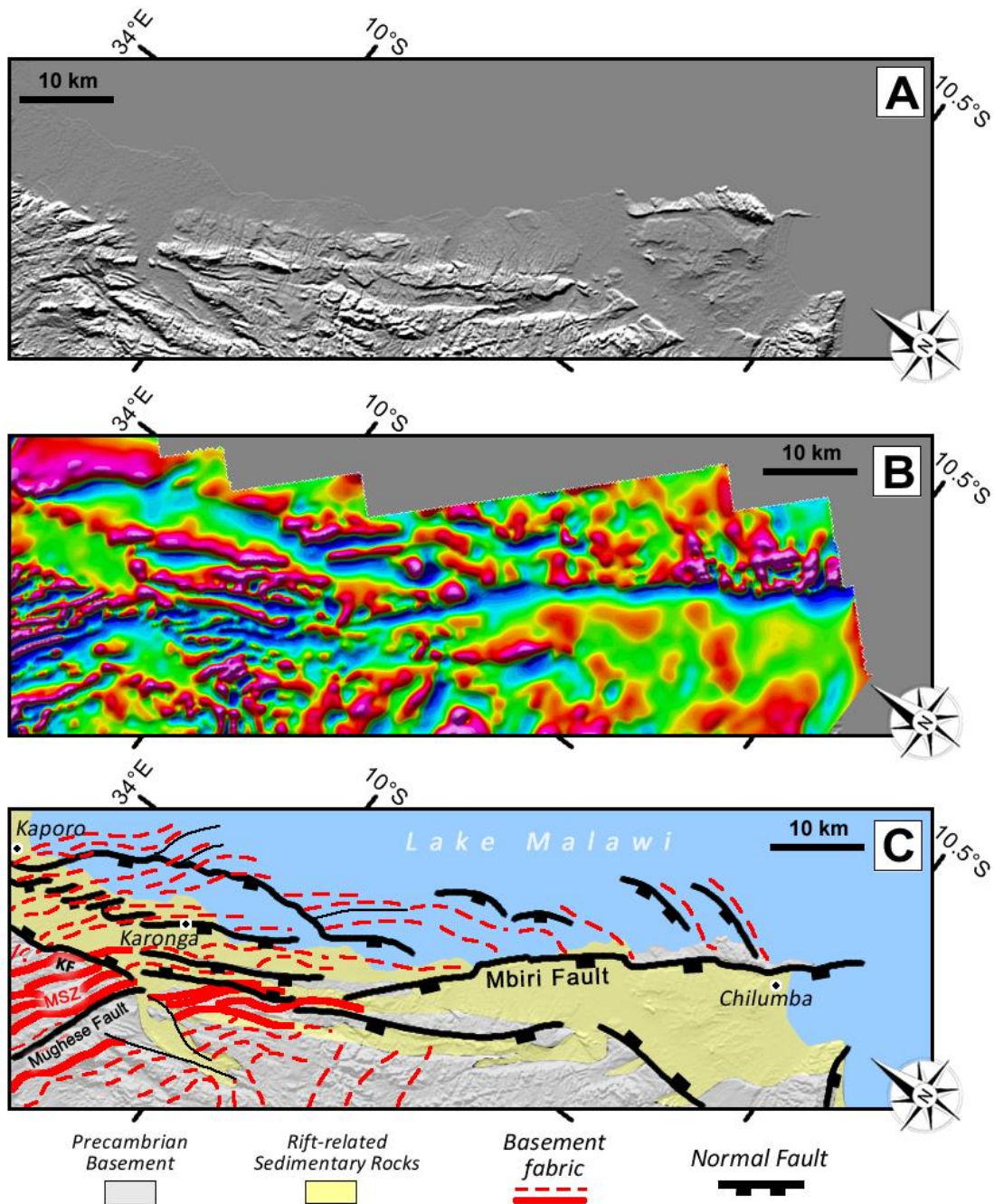


Fig. 9. The SW margin of the North Malawi Rift Basin (Karonga area). Topographic digital elevation model in the top panel (A), the vertical derivative of the magnetic data in the middle panel (B), and a structural interpretation in the bottom panel (C). MSZ = Mughese Shear Zone, KF = Karonga Fault. Fault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

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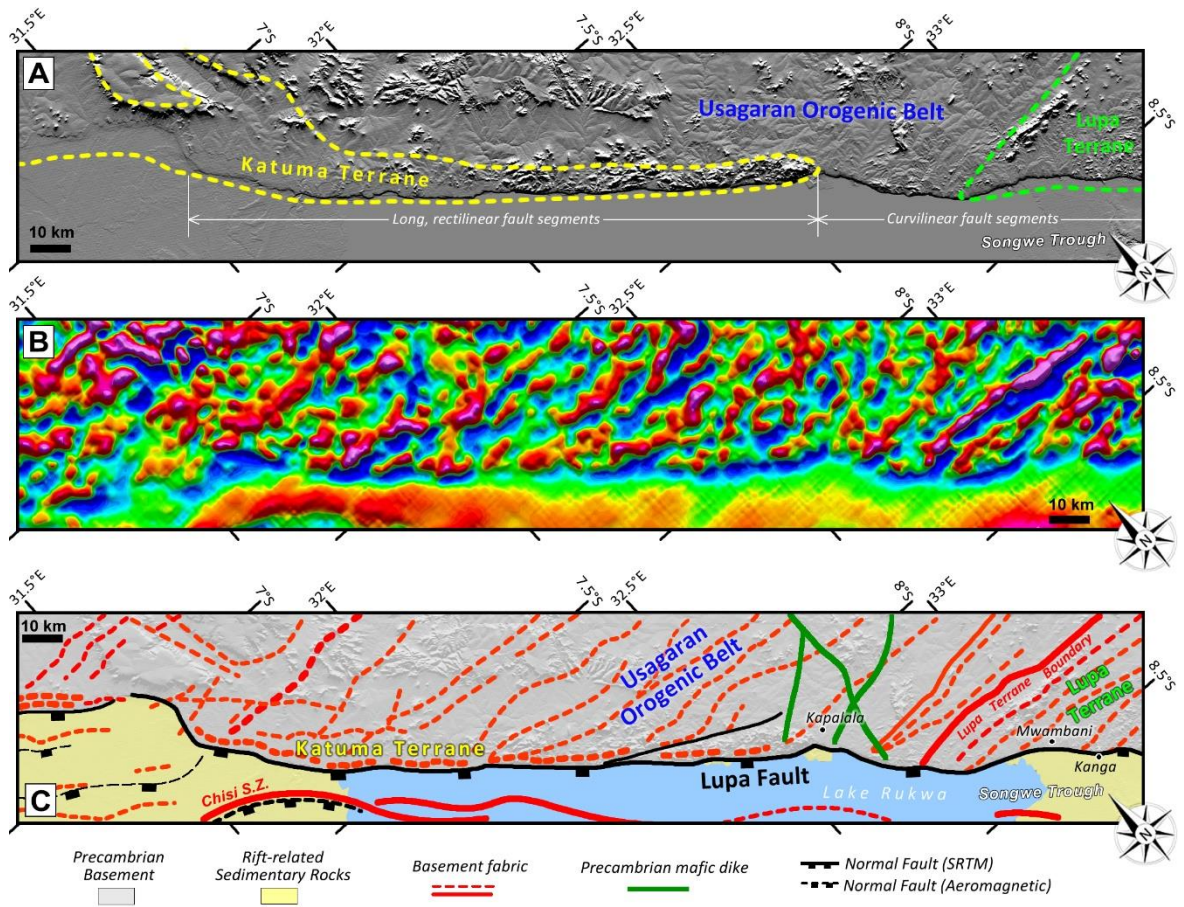


Fig. 10. The northern section of the Lupa Fault, the NE boundary fault of the Rukwa Rift. Topographic digital elevation model in the top panel (A), the vertical derivative of the magnetic data in the middle panel (B), and a structural interpretation in the bottom panel (C).

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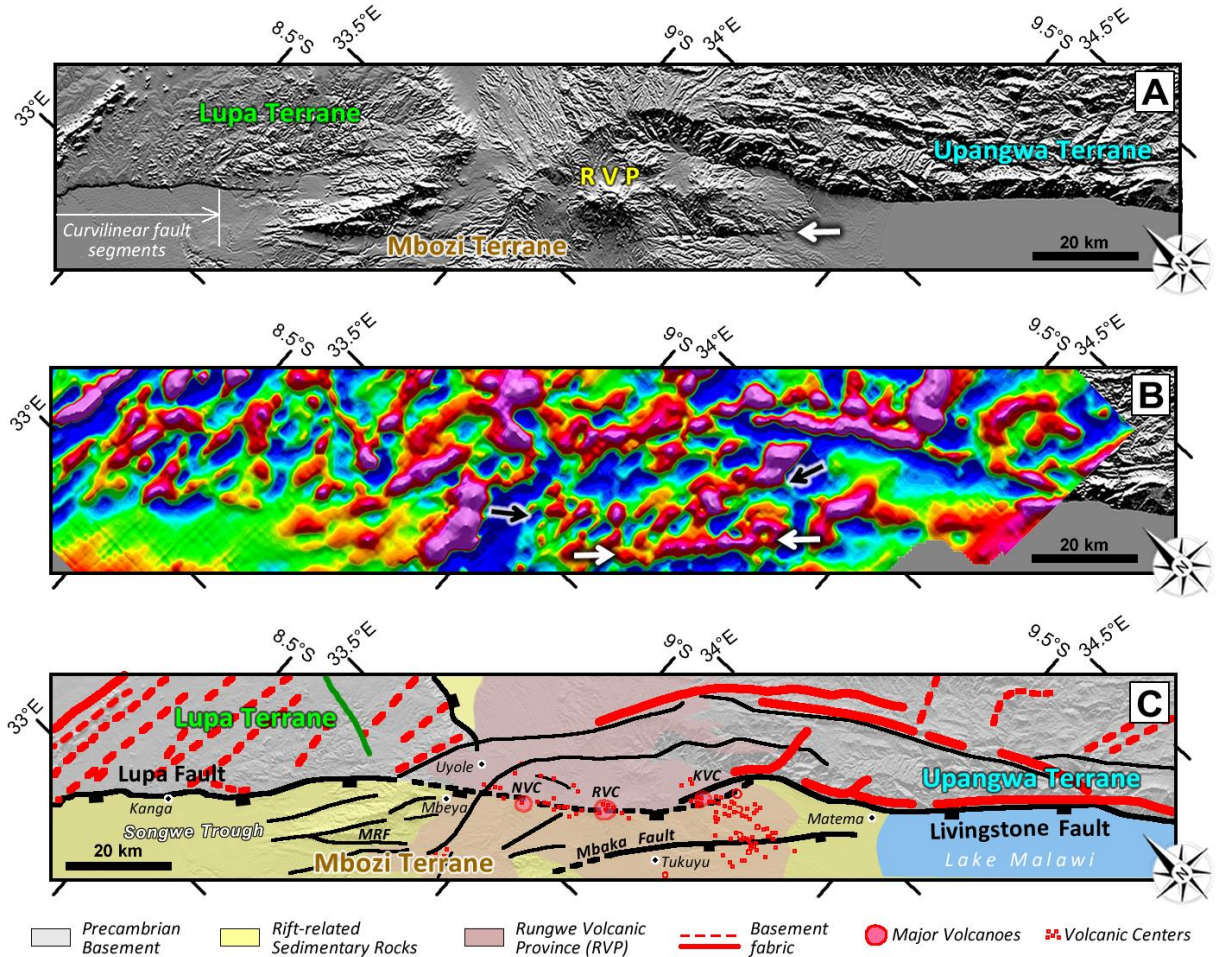


Fig. 11. The southern section of the Lupa Fault, the NE margin of the Mbozi Block (Rungwe Volcanic Province) and a section of the Livingstone Fault (NE border fault if the North Malawi Rift). Topographic digital elevation model in the top panel (A), the vertical derivative of the magnetic data in the middle panel (B), and a structural interpretation in the bottom panel (C). KVC = Kyejo Volcanic Center; NVC = Ngozi Volcanic Center; RVC = Rungwe Volcanic Center. Volcanic centers from Fontijn et al. (2010, 2012).

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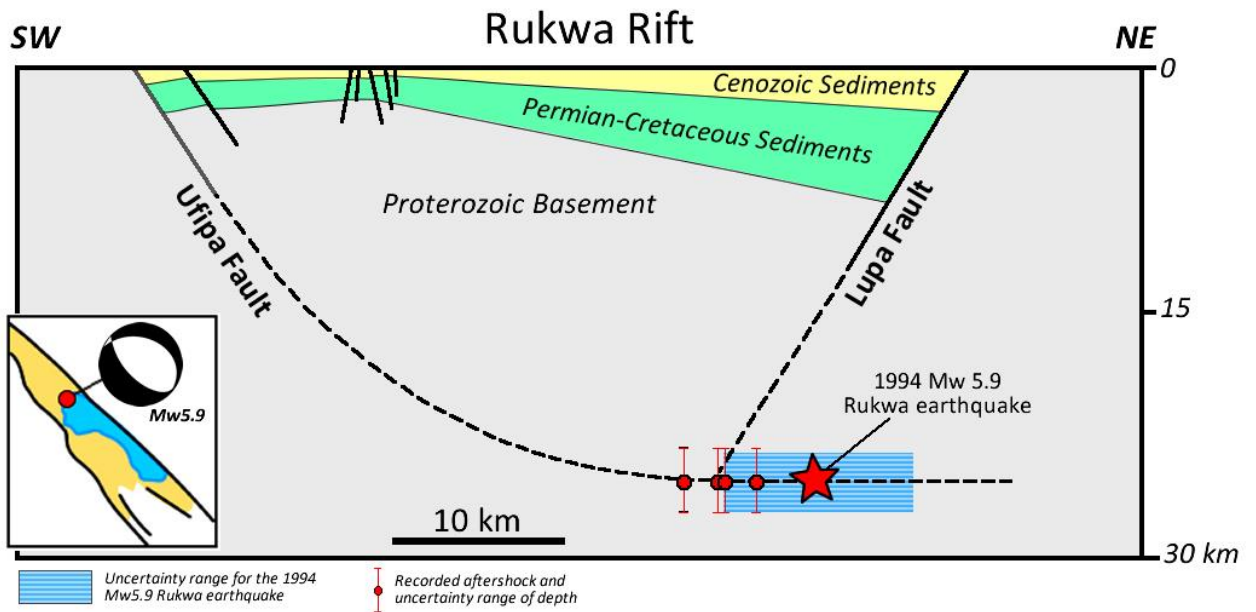


Fig. 12. Generalized geometrical relations of stratigraphic units and normal faults of the Rukwa rift, showing thickening of Cenozoic sediments towards both the Lupa and Ufipa border faults (modified after Zhao et al., 1997).

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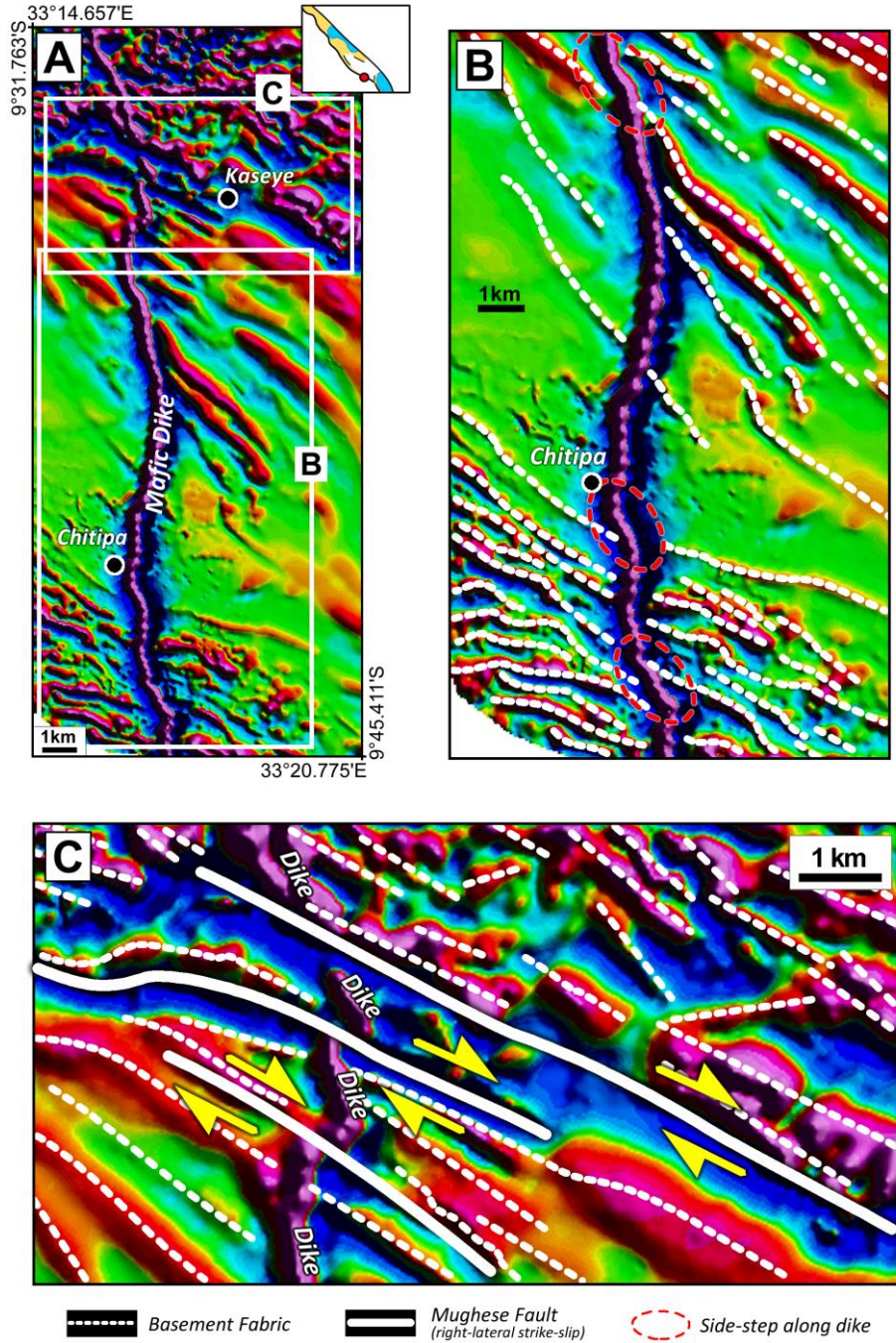


Fig. 13. (A) 1st vertical derivative of the aeromagnetic data covering the Kaseye-Chitipa area along the SW margin of the Mbozi Block (see location in top-right inset map, Figures 4A-B and 8C). (B) Close-up of the central and southern segments of a buried mafic dike (the “Chitipa Dike”) showing side-stepping 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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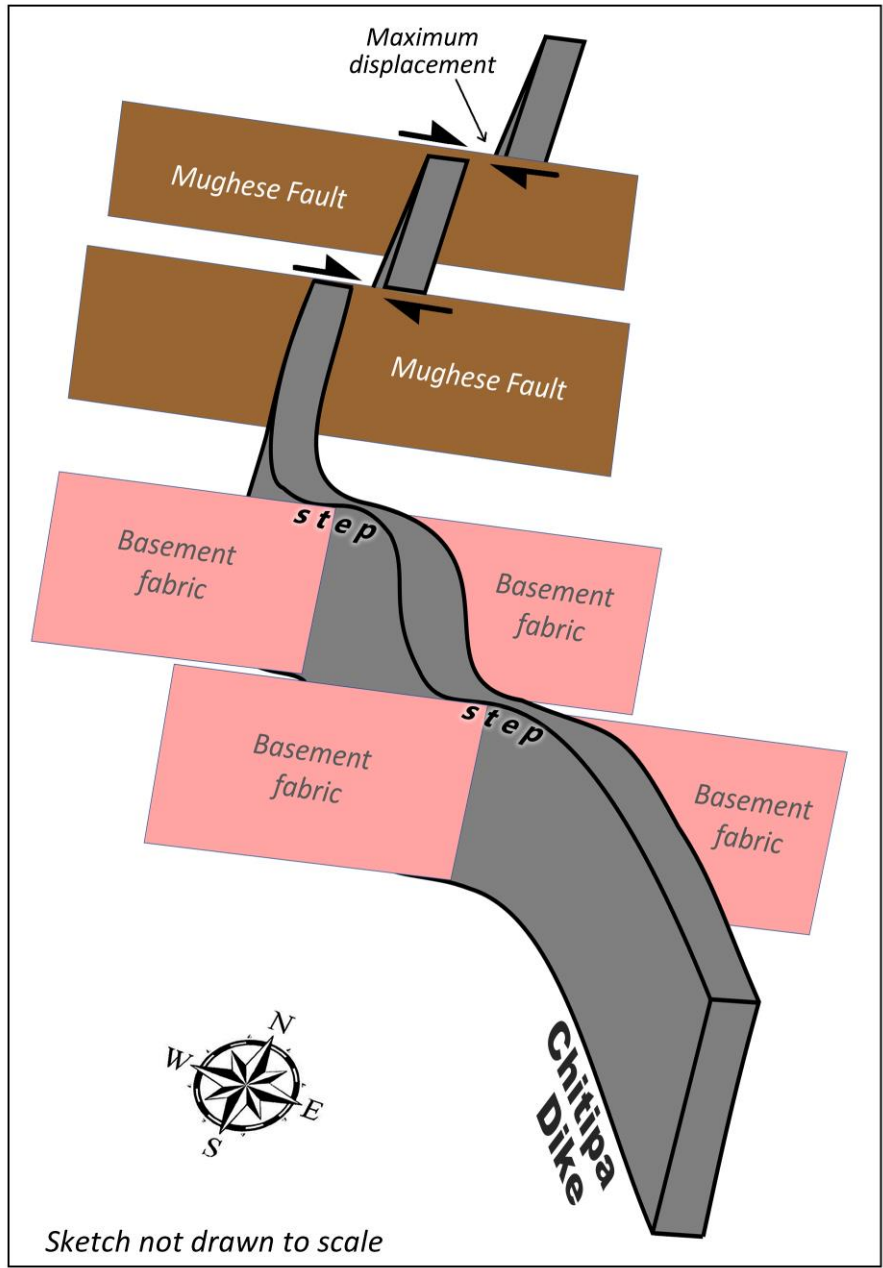


Fig. 14. 3-dimensional (3-D) conceptual model of the geometry of the interpreted dike (the “Chitipa Dike”) and its interactions with the pre-existing basement fabric and the post-emplacement Mughese strike-slip fault offset.

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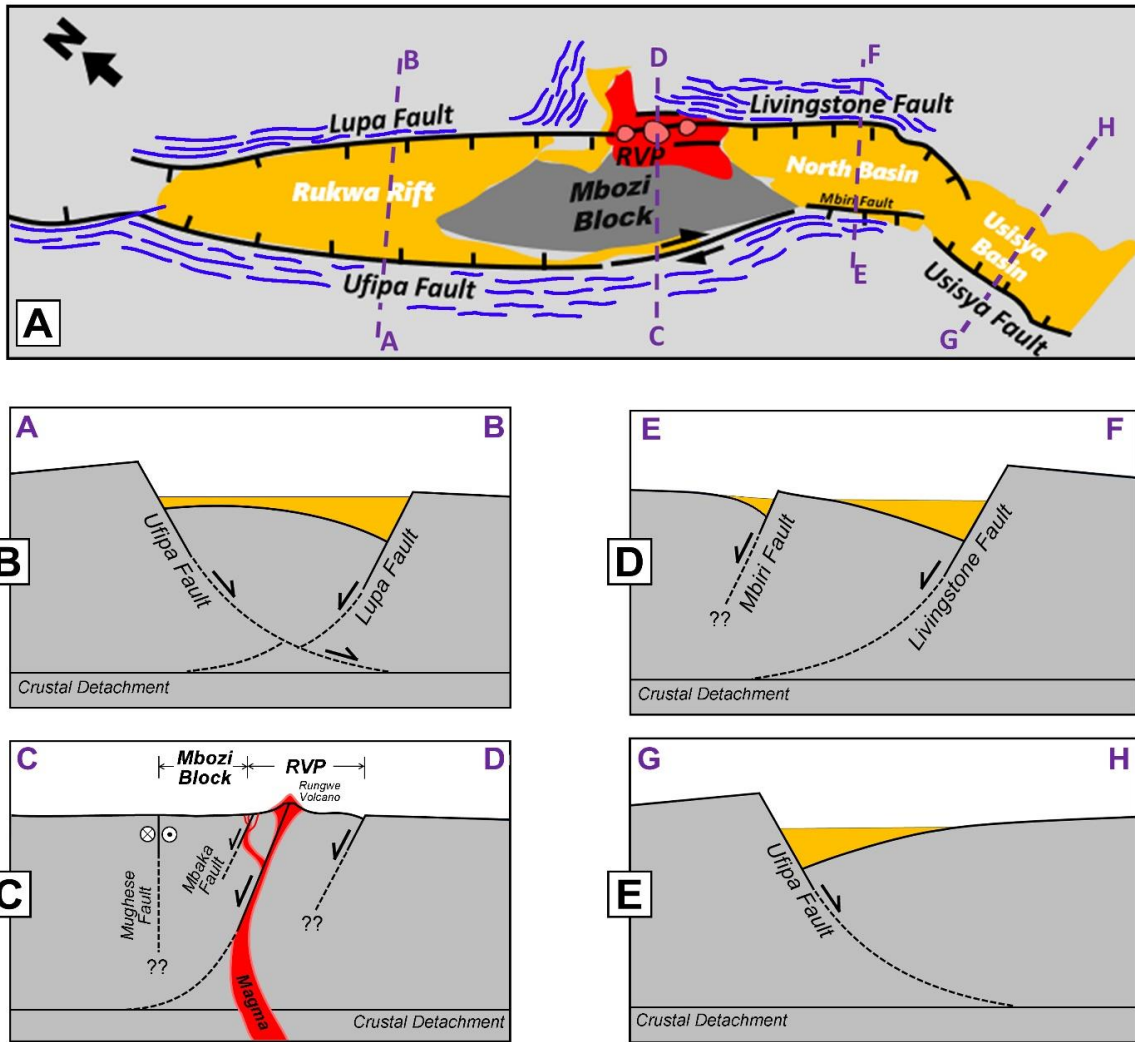


Fig. 15. (A) Generalized cartoon (map view) of the Rukwa-North Malawi Rift Segment (RNMR) illustrating the continuous structural connectivity along the northeast and southwest boundaries, guided by the basement fabric. Black solid line = fault, blue solid line = basement fabric. RVP = Rungwe Volcanic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

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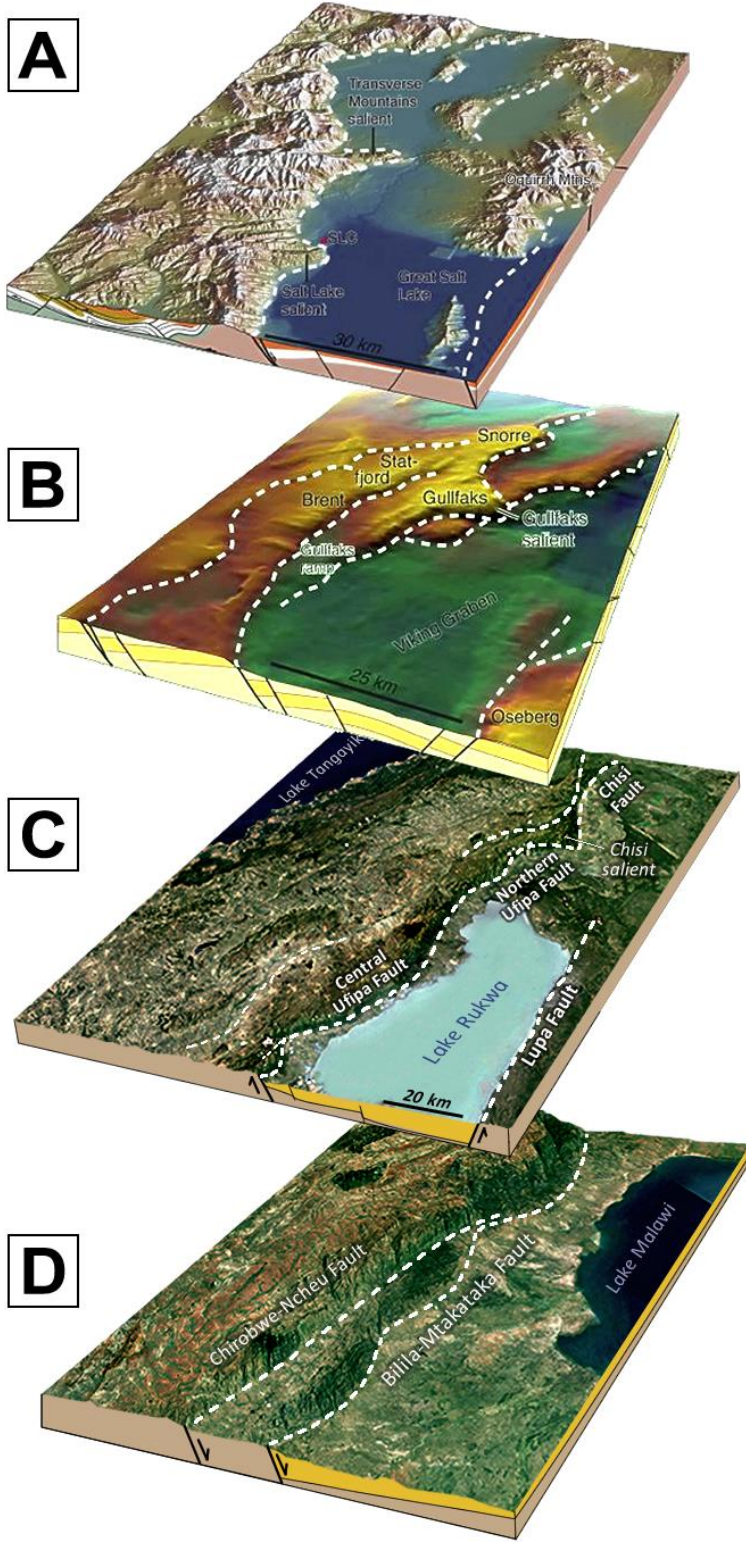


Fig. 16. (A-B) The Wasatch Fault in the Salt Lake area, Utah, and the first-order faults in the northern North Sea (base Cretaceous unconformity) showing concave-curvilinear fault geometries (modified after Fossen and Rotevatn, 2016). (C) Strikingly similar Concave-curvilinear fault geometry occurs in 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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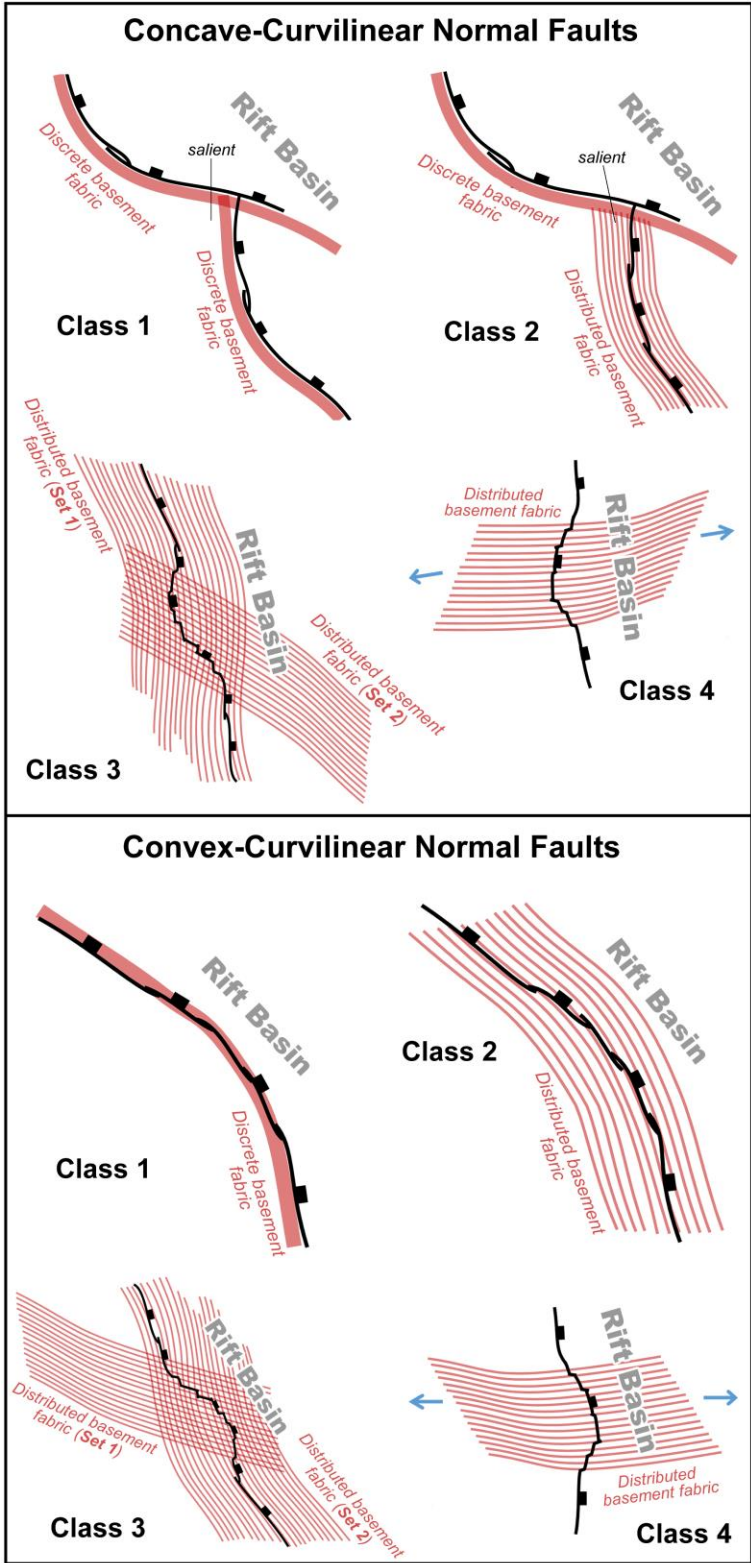
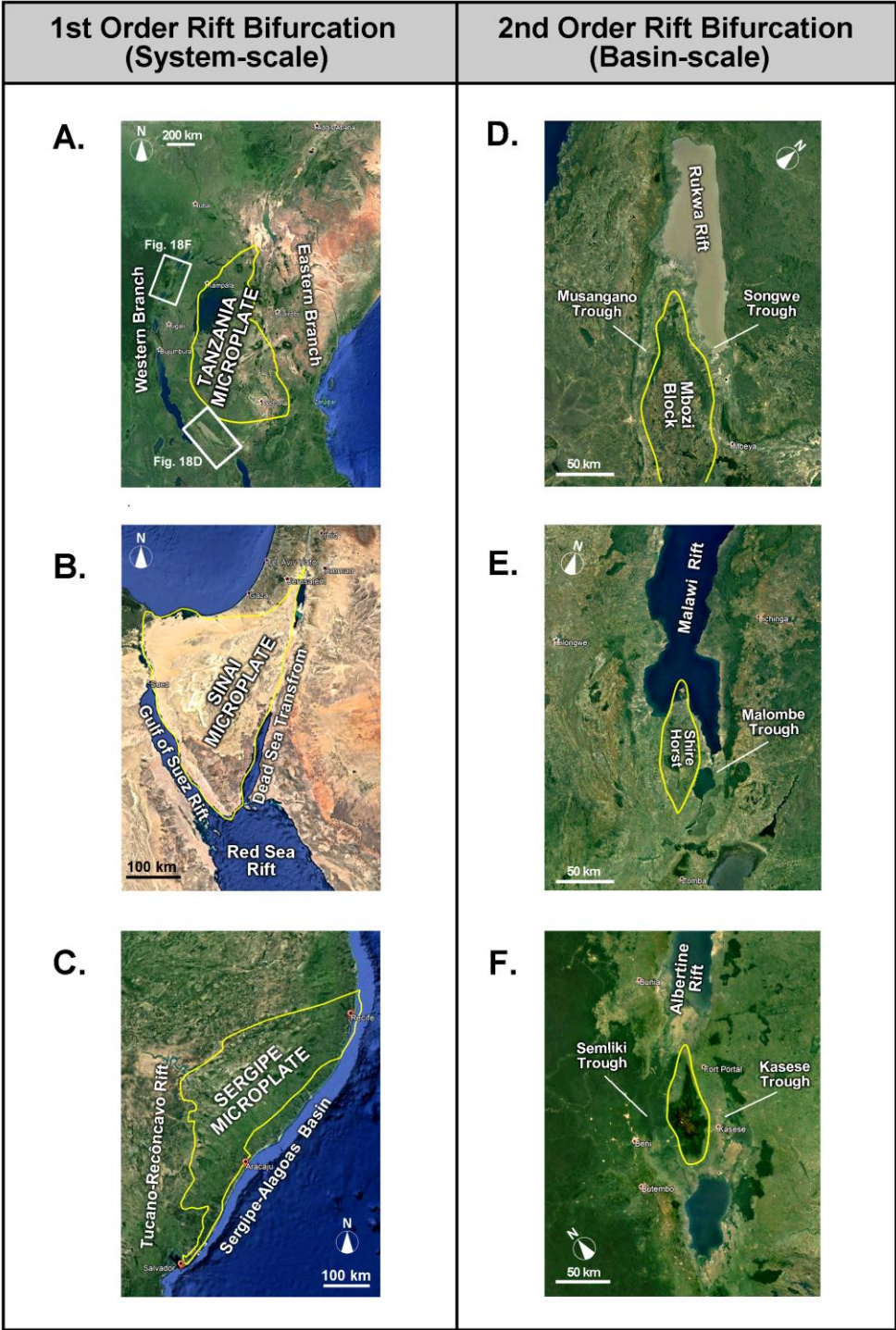


Fig. 17. Models illustrating the control of varying configurations of pre-existing basement fabrics on the development of concave- and convex-curvilinear normal fault plan-view geometries. These models are based on the observations from the Rukwa – North Malawi Rift Segment (this study).

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1791 Fig. 18. Examples of system-scale rift bifurcation in the (A) East African Rift System, (B) Red
 1792 Sea Rift and (C) South Atlantic Rift; and examples of basin-scale rift bifurcation in the (D)
 1793 Rukwa Rift (see Fig. 18A for location), (E) southern Malawi Rift and (F) Albertine Rift (see Fig.
 1794 18A for location). These examples show that the 2nd order bifurcations are integral components
 1795 of inter-rift transfer zones where the coupling of rift segments take place.