

 Open access • Posted Content • DOI:10.3389/FEART.2021.707869

Structural Inheritance Controls Strain Distribution During Early Continental Rifting, Rukwa Rift — [Source link](#)

Folarin Kolawole, Thomas Phillips, Estella A. Atekwana, Christopher A.-L. Jackson

Published on: 13 May 2021 - Frontiers in Earth Science (EarthArXiv)

Topics: Rift, Shear zone, Fault (geology) and Terrane

Related papers:

- [Early Structural Development of the Okavango Rift Zone, NW Botswana](#)
- [Fault architecture in the Main Ethiopian Rift and comparison with experimental models: Implications for rift evolution and Nubia–Somalia kinematics](#)
- [Evolution of upper crustal faulting assisted by magmatic volatile release during early-stage continental rift development in the East African Rift](#)
- [The influence of preexisting structure on the evolution of the Cenozoic Malawi rift \(East African rift system\)](#)
- [Comparing extension on multiple time and depth scales in the Corinth Rift, Central Greece](#)

Share this paper:    

View more about this paper here: <https://typeset.io/papers/structural-inheritance-controls-strain-distribution-during-4k2arno6e4>

1 **This manuscript is a minor revision of an earlier preprint** and has been re-submitted for publication in
2 **Frontiers in Earth Science**. It is our expectation that **it will hopefully be accepted for publication**.
3 Subsequent versions of this manuscript may differ due to editorial process. If accepted for publication, the final
4 version will be available through the “Peer-reviewed publication DOI” link on EarthArXiv.
5 We hope you find this paper interesting and would welcome your feedback on it. Kindly contact Folarin
6 Kolawole (folarin.kol@gmail.com) with your feedback.

7

8 **Structural Inheritance Controls Strain Distribution During** 9 **Early Continental Rifting, Rukwa Rift**

10
11 **Folarin Kolawole^{1,2*}, Thomas B. Phillips³, Estella A. Atekwana⁴ and Christopher A-L.**
12 **Jackson⁵**

13 *¹School of Geosciences, University of Oklahoma, 100 East Boyd Street, RM 710, Norman, Oklahoma*
14 *73019*

15 *²Now at BP America, 501 Westlake Park Blvd, Houston, TX 77079*

16 *³Department of Earth Sciences, Durham University, Science Labs, Durham DH1 3LE*

17 *⁴Department of Earth Science, University of Delaware, 101 Penny Hall, Newark, Delaware 19718*

18 *⁵Department of Earth and Environmental Sciences, The University of Manchester, Williamson Building,*
19 *Oxford Road, Manchester, M13 9PL, UK*

20
21 *Corresponding Author: F. Kolawole (folarin.kol@gmail.com)
22

23 **ABSTRACT**

24 Little is known about rift kinematics and strain distribution during the earliest phase of extension
25 due to the deep burial of the pre-rift and earliest rift structures beneath younger, rift-related
26 deposits. Yet, this exact phase of basin development ultimately sets the stage for the location of
27 continental plate divergence and breakup. Here, we investigate the structure and strain distribution
28 in the multiphase Late Paleozoic-Cenozoic magma-poor Rukwa Rift, East Africa during the
29 earliest phase of extension. We utilize aeromagnetic data that image the Precambrian Chisi Shear
30 Zone (CSZ) and bounding terranes, and interpretations of 2-D seismic reflection data to show that,
31 during the earliest rift phase (Permo-Triassic ‘Karoo’): (1) the rift was defined by the Lupa Fault,
32 which exploited colinear basement terrane boundaries, and a prominent intra-basinal fault cluster
33 ($329^\circ \pm 9.6$) that trends parallel to and whose location was controlled by the CSZ (326°); (2)
34 extensional strain in the NW section of the rift was accommodated by both the intra-basinal fault
35 cluster and the border fault, where the intra-basinal faulting account for up to 64% of extension;
36 in the SE where the CSZ is absent, strain is primarily focused on the Lupa Fault. The early-rift
37 strain in the Rukwa Rift is thus, not accommodated only by border the fault as suggested by

38 existing magma-poor early-rift models; instead, strain focuses relatively quickly on a large border
39 fault and intra-basinal fault clusters that follow pre-existing intra-basement structures; (3) two
40 styles of early-phase strain localization are evident, in which strain is localized onto a narrow
41 discrete zone of basement weakness in the form of a large rift fault (Style-1 localization), and onto
42 a broader discrete zone of basement weakness in the form of a fault cluster (Style-2 localization).
43 We argue that the CSZ and adjacent terrane boundaries represent zones of basement mechanical
44 weakness that controlled the first-order strain distribution and rift development during the earliest
45 phase of extension. The established early-rift structure, modulated by structural inheritance, then
46 persisted through the subsequent phases of rifting. The results of our study, in a juvenile, and
47 relatively well-exposed and data-rich rift, are applicable to understanding the structural evolution
48 of deeper, buried ancient rifts.

49

50

51 *Keywords: Continental Rifting, Tectonic Strain, Normal Faults, Rukwa Rift, Shear Zones, East*
52 *African Rift System*

53 INTRODUCTION

54 Tectonic extension of the continental lithosphere is typically accommodated by the brittle
55 deformation of the upper crust, demonstrated by the emergence of normal fault populations (Cowie
56 et al., 2005; Agostini et al., 2011; Muirhead et al., 2016, 2019). Some classic models for the
57 evolution of continental rifts, suggest that during the early phase of extension, strain is initially
58 accommodated by the development of distributed normal faults, with strain subsequently
59 localizing onto a few large faults and subsequently migrating to the rift axis (e.g., Gawthorpe and
60 Leeder, 2000; Cowie et al., 2005; Nixon et al., 2016; Naliboff et al., 2017). However, a comparison
61 of juvenile, magma-rich and magma-poor segments of narrow rifting along the East African Rift
62 System (EARS) show that in contrast to the magma-rich rift basins where strain is accommodated
63 by both the large basin-bounding faults (border faults) and intra-basinal structures, the border
64 faults accommodate most (~90 %) of the strain in the magma-poor rift segment (Muirhead et al.,
65 2019). Elsewhere along the EARS, the incipient (<3 Ma) magma-poor Zomba Graben, southern
66 Malawi Rift, has already witnessed the localization of strain in the rift axis, with the related faults
67 presently accounting for up to 55 % (± 24) of the extensional strain (Wedmore et al., 2020). The
68 evidence presented in these studies indicate that early-phase extensional strain along magma-poor
69 continental rifts may or may not be primarily accommodated by only the border faults. Thus, there
70 is a need to better understand other mechanisms that can facilitate early focusing of intra-basinal
71 faulting and extensional strain in magma-poor continental rifts.

72 Since continental rifts typically develop in previously deformed lithosphere (Wilson, 1966; Dewey
73 and Spall, 1975; Buiter and Torsvik, 2014), the distribution of early-phase strain in magma-poor
74 rifts can be complex due to the interaction between faults that exploit or reactivate pre-existing
75 structures, and those that form independently of any pre-existing structure (e.g., Manatschal et al.,

76 2015; Kolawole et al., 2018; Ragon et al., 2019; Schiffer et al., 2019; Phillips et al., 2019a,b;
77 Heilman et al., 2019; Osagiede et al., 2020; Wang et al., 2021). Overall, very little is known about
78 the earliest phase of continental extension, and even less of how strain is partitioned along inherited
79 structures; this reflects the fact that the associated structures and related stratigraphic record are
80 typically deeply buried beneath younger (i.e., post-rift or later rift phase) sequences and are thus
81 difficult to image with geophysical data, or are overprinted by later tectonic events (e.g., post-rift
82 plate collision). This knowledge gap limits a fuller understanding of the spectrum of processes that
83 govern continental rifting and breakup in space and time.

84 The EARS (Fig. 1A) is the largest active continental rift system on Earth. This system, which
85 formed by the stretching of previously deformed lithosphere, is characterized by segments that
86 span the major stages of continental rifting from inception to transitional crust (e.g., Daly, 1989;
87 Hayward & Ebinger, 1996; Delvaux, 2001; Ebinger, 2005; Chorowicz, 2005). We integrate
88 available geophysical and geological datasets from the multiphase magma-poor Rukwa Rift (Figs.
89 1A-B, 2A-D) to explore how strain was distributed during the earliest phase of extension, and
90 investigate the dominant controls. We show that the potentially lithosphere-scale Precambrian
91 Chisi Shear Zone (CSZ) and its adjacent terrane boundaries (Fig. 1B; Lemna et al., 2019; Heilman
92 et al., 2019) represent major zones of pre-rift basement mechanical weakness that controlled the
93 location, structure, and evolution of both the border and intra-basinal faults during the earliest
94 phase of continental extension. We show how the geometry of the CSZ controlled along-rift
95 variations in the early-phase tectonic extension and overall basin geometry, the effects of which
96 persist through and thus influence the later rift geometry. We also expand our analysis to the nearby
97 Luama Rift (located in DRC), which is coeval, colinear with, and parallel to the Rukwa Rift; both
98 basins representing structural elements along a NW-trending Karoo-age rift branch herein referred

99 to as “the Rukwa Trend” (Fig. 1A). Our results resolve a long-standing controversy related to the
100 geometrical structure and kinematics of rifting in this part of the East African Rift System.

101

102 **GEOLOGICAL SETTING**

103 *The Precambrian (Pre-Rift) Basement of the Rukwa Trend*

104 The crystalline basement of the Rukwa Trend is composed of the metamorphic and igneous rocks
105 of the Precambrian (1.95 -1.85 Ga) Ubendian Belt, which formed during the collision of the
106 Archean Tanzania Craton and the Bangweulu Block, and which comprises the Ufipa, Katuma,
107 Wakole, Lupa, Mbozi, Ubende, and Upangwa terranes (Figs. 1A-B; Daly, 1988; Lenoir et al.,
108 1994). This orogenic belt, which is defined by several NW-trending terranes (2.1-2.025 Ga) that
109 are bounded by steeply dipping, ductile, amphibolite facies, strike-slip shear zones (Fig. 1B; Daly,
110 1988; Lenoir et al., 1994; Theunissen et al., 1996; Kolawole et al., 2018). The terranes are
111 composed of amphibolite to granulite facies gneisses with foliations that dominantly trend NW-
112 SE and commonly steepen near the terrane boundaries (Lenoir et al., 1994). Although relative rare
113 compared to gneisses, other metasediments along the belt consists of mica schists, marbles, meta-
114 anorthosites, and ferruginous quartzites (Lenoir et al., 1994).

115 The geochronology, geochemistry, and metamorphic structure of the Ubendian Belt suggests that
116 it formed in response to multiple episodes of wrench tectonic events (Theunissen et al., 1996) with
117 phases of subduction extending from the Paleoproterozoic to the Neoproterozoic (Ganbat et al.,
118 2021). The orogenic belt first developed during a phase of collisional orogeny along the SW
119 margin of the Tanzanian Craton (ca 2.1 - 2.0 Ga), after which the belt experienced two episodes

120 of wrench tectonics consisting of an initial phase of dextral strike-slip shear at ca. 1.8 – 2.0 Ga,
121 followed by a ductile-brittle sinistral strike-slip reactivation in the Neoproterozoic (Lenoir et al.,
122 1994). This Neoproterozoic shear reactivation recorded the development of thick mylonite and
123 blastomylonite zones with low-grade metamorphic assemblages along shear zones that bound the
124 terranes. The terranes and associated fabrics which are observable in basement exposures along
125 the flanks of the Phanerozoic Rukwa Rift, are suggested to have exerted some control on the
126 development of the basin (Wheeler and Karson, 1994; Theunissen et al., 1996; Klerkx et al., 1998;
127 Boven et al., 1999; Lemna et al., 2018; Heilman et al., 2019).

128

129 *The Chisi Shear Zone (CSZ)*

130 Along the Ubendian Belt, the Chisi Shear Zone (CSZ) is a prominent shear zone which separates
131 the Ufipa Terrane to the southwest, from the Wakole and Ubende Terranes to the northeast (Fig.
132 1B). The structure was initially identified as the “Ikulu series” or “Ikulu Terrane”, a broad (6 - 12
133 km-wide in Chisi area) shear belt composed of amphibolite, micaschist, and meta-calcareous rocks
134 with high pressure blueschist or eclogitic associations (Lenoir et al., 1994; Boven et al., 1999).
135 The mafic high-pressure sequences along the shear zone were interpreted to represent disrupted
136 remnants of deeply subducted ophiolites (Smirnov et al., 1973; Lenoir et al., 1994; Klerkx et al.,
137 1997; Sklyarov et al., 1998).

138 Along the ‘Ikulu’ structure, amphibolites and amphibole gneisses exhibit metamorphic foliation
139 with planes that dominantly strike WNW-ESE and dip steeply to the NNE and S-SSW
140 (stereographic plot with red filled circles in Fig. 2A; Theunissen et al., 1996; Boven et al., 1999).
141 The rocks also exhibit mineral elongation lineation and some fold axes of asymmetric intrafolial

142 folds that generally trend NW-SE and plunge shallowly-to-moderately to the ESE-SE
143 (stereographic plot with open diamonds in Fig. 2A). Mylonitic rocks along the SW margin of the
144 granulitic Ubende Terrane exhibit P-T characteristics and shear fabrics suggesting an uplift and
145 exhumation of the terrane relative to the felsic Ufipa Terrane on the SW flank of the ‘Ikulu’
146 structure (Theunissen et al., 1996; Sklyarov et al., 1998; Boven et al., 1999). More detailed
147 petrographic and geochemical investigation of the eclogites reveal striking similarities with
148 oceanic island-arc volcanic rocks (Boniface & Schenk, 2012). Geochronologic analyses indicate a
149 clustering of Paleoproterozoic eclogites to the northern segment of the structure (near Lake
150 Tanganyika) and Neoproterozoic eclogites to the south (e.g., Chisi area and northern Malawi) (Fig.
151 1B), suggesting multiple cycles of subduction-related orogenic events along the structure
152 (Boniface & Schenk, 2012; Boniface et al., 2012; Ganbat et al., 2021). Thus, the ‘Ikulu’ domain
153 was proposed to be the primary Late Proterozoic (Pan African Orogeny) suture zone between the
154 Tanzania and Bangweulu Cratons along the Ubendian Belt (Boniface & Schenk, 2012).

155 Further, the magnetic-high anomaly expression of the ‘Ikulu’ domain, created by the dominance
156 of mafic rocks along the belt, defines a prominent regional magnetic lineament that extends
157 southeast beneath the Rukwa Rift sedimentary cover, sub-parallel to the northwest trend of the rift
158 (Figs. 1B; Lemna et al., 2019; Heilman et al., 2019). Since the Chisi area of Tanzania represents a
159 type-locality for the detailed studies of the structural fabrics, geochemistry, and petrology of the
160 structure (Theunissen et al., 1996; Boven et al., 1999; Boniface & Schenk, 2012), the structure was
161 recently officially re-introduced as “Chisi Shear Zone” (Lemna et al., 2019) or “Chisi Suture Zone”
162 (Heilman et al., 2019). However, in this current study, we adopt the name “Chisi Shear Zone” to
163 refer to the structure.

164

165 ***Phanerozoic Rifting along the Rukwa Trend***

166 The present-day configuration of the Rukwa Trend consists of multiple colinear, NNW-trending
167 rift basins (Rukwa, Karonga, and Luama basins) that initially developed during Permo-Triassic
168 (Karoo) phase of rifting (e.g., Delvaux, 2001). All three basins were reactivated by extensional
169 tectonics in the Cretaceous (Roberts et al., 2010, 2012). However, only the Rukwa Rift and
170 Karonga Basin (Fig. 1A) experienced significant reactivation in the Cenozoic, and they are still
171 currently active (e.g., Morley et al., 1999; Delvaux, 2001; Chorowicz, 2005). The Rukwa Rift, the
172 primary focus of this study, currently defines a graben and is bounded to the northeast by the Lupa
173 Fault and to the southwest by the Ufipa Fault (Fig. 2B; Heilman et al., 2019; Morley et al., 1999).
174 The basin initially developed as a NE-dipping half graben (with a shallow graben geometry only
175 in the NW) during the Karoo rifting phase, bounded to the northeast by the principal border fault,
176 the Lupa Fault (Figs. 2C-D). The Karoo intra-basinal faults (KIF) and basement highs
177 predominantly trend NNW, oblique to the Lupa Fault strike (Fig. 2B). Estimates of the Karoo-age
178 extension direction vary from NE-SW to E-W (Fig. 2B).

179

180 **DATASET AND METHODOLOGY**

181 Along the Rukwa Trend, we compile structural mapping and structural measurement data from
182 published 2-D seismic data (e.g., Fig. 2C; Morley et al., 1999) and integrate these with
183 aeromagnetic data (Figs. S1A-B) and satellite radar digital elevation model (DEM) (Figs. S2A-B).

184

185 *Aeromagnetic Data, Satellite Topographic Data, and their Analyses:*

186 We use aeromagnetic data to map key pre-rift intra-basement structures along the axis of the
187 Rukwa Rift and along-trend of the rift. We applied derivative filters to the aeromagnetic grid to
188 enhance structural features (Fig. 3A), and mathematical transforms to estimate the depths to
189 magnetic sources in the basement (Figs. 3B-D; see supplementary information).

190 The aeromagnetic data (Fig S1A), collected between 1977-1980 with flight height of 200 m and a
191 flight line spacing of 1 km, was provided by the South African Council for Geoscience. First, we
192 reduced the data to the magnetic pole (RTP) to correct for latitude-dependent skewness (Baranov,
193 1957), after which we applied a vertical derivative filter to better resolve magnetic gradients
194 associated with structural features (Figs. 3A, S1B) (Salem et al., 2007; Kolawole et al., 2017, 2018;
195 Heilman et al., 2019). In this study, we delineate the boundaries of the Chisi Shear Zone along the
196 edges of the high magnetic anomaly lineament in the vertical derivative map of the aeromagnetic
197 grid. In areas where aeromagnetic data is not available, we augmented the basement mapping with
198 30 m-resolution Satellite Radar Topographic Mission (SRTM) Digital Elevation Model (DEM)
199 hill shade maps (Figs. S2A-B).

200

201 *Structural Data from Seismic Interpretation:*

202 We establish the initial (i.e., Karoo rift phase) geometry of the Rukwa Rift and related faults using
203 published seismic reflection profiles, and associated fault trace maps and sediment thickness maps
204 ('Karoo Isopach') presented by Morley et al. (1992, 1999). We also calculate along-rift variations
205 in Karoo-age tectonic extension (backstripped to Karoo time surface; Figs. 4A-D) accommodated
206 by slip on the Lupa Fault and intra-basinal faults, again using data published by Morley et al.
207 (1992). We integrate these structural data with aeromagnetic data analysis to investigate the

208 influence of the pre-rift basement structure on the early-rift structure and evolution of the Rukwa
209 Rift (Figs. 4A-C).

210

211 **RESULTS**

212 *3-D Geometry and Extent of the CSZ*

213 The petrology and geochemistry, local structure, and topographic expression of the CSZ is well-
214 constrained in the Chisi area, located on the NW flank of the Rukwa Rift (Figs. 1B and 2A;
215 Theunissen et al., 1996 and Boven et al., 1999; Boniface & Schenk, 2012). Field observations
216 show that the CSZ is dominated by steep, NE- and SW-dipping, metamorphic fabrics hosted by
217 eclogite facies rocks (Fig. 2A). At this location, the CSZ is characterized by a prominent NW-
218 trending, positive magnetic anomaly lineament (Fig. 1B) and a topographic ridge (Figs. 2A and
219 S2A). Based on its distinct geophysical and geomorphic expression, as well as known field
220 locations of eclogite rocks, we map the northwestward and southeastward continuations of the
221 CSZ system beneath the Rukwa Rift and along the northeastern boundary zone of the Luama Rift
222 respectively (Fig. 1B).

223 Northwest of the Chisi area, the CSZ associated structures are colinear with the subaerial Mahale
224 Ridge and the submerged Kavala Island Ridge (submerged beneath Lake Tanganyika), and
225 continues northwest into the Busindi Ridge which itself represents the footwall of the Busindi
226 border fault of the Luama Rift (Fig. 1B, S2A). Along the Luama Rift, the inferred CSZ extension
227 represents the boundary between the Kibaran Belt (to the south) and the Ruzizian Belt to the north
228 (Fig. 1A). Based on the occurrence of a prominent high magnetic lineament extending NNW
229 across Lake Tanganyika from the northernmost known CSZ-related eclogite exposure, a possible

230 East CSZ splay is delineated to continue northward and link with the N-trending Ubwari Ridge
231 (buried horst and subaerial peninsula; Figs. 1B, S1A-B). Although the Ubwari Ridge is a fault-
232 bounded horst block in the Cenozoic Tanganyika Rift, its possible spatial association with the CSZ
233 inferred based on both the colinearity with the continuation of the magnetic-high anomaly
234 lineament of the CSZ, and the southeastward rotation of the N-trending metamorphic fabrics of
235 the subaerial section of the horst (Figs. S1B and S2B).

236 The CSZ extends southeastwards from the Chisi area to continue beneath the Rukwa Rift, where
237 it is sub-parallel to the rift border faults (Figs. 1B and 2A). Just southeast of the termination of the
238 CSZ magnetic lineament, the >15 km-wide Mughese Shear Zone (MSZ) which separates the Ufipa
239 and Mbozi Terranes of the Ubendian Belt (Fig. 1B), extends beneath the Msongano Trough
240 (bifurcation of the Rukwa Rift) and continues southeast into the Karonga Basin (Figs. 1B, 2B).
241 Overall, the CSZ-associated aeromagnetic and geomorphic structures extend for >600 km from
242 the Luama and Tanganyika rifts, southeastwards through the Rukwa Rift (Fig. 1B). Although our
243 mapping suggests an along-trend and perhaps genetic relationship between the CSZ and the
244 Mughese Shear Zone (Fig. 1B), we clarify that at the time of this contribution, there is no available
245 data demonstrating that the Mughese Shear Zone is also a subduction-related suture. In the absence
246 of this information, we define the southeast termination of the CSZ as the termination zone of its
247 magnetic anomaly lineament beneath the Rukwa Rift (Figs. 1B and 3A).

248 Our 3D grid of the depth-distribution of intra-basement magnetic sources along the Rukwa Rift
249 (Figs. 3A-C, S3A-B, S4A-B) reveal a steeply-dipping, NW-trending zone of magnetic sources that
250 extend to 12 km depth; this feature is spatially collocated with the surface trend of the CSZ
251 aeromagnetic lineament (Fig. 3B). Northeast of these CSZ-related magnetic sources, a narrow sub-
252 vertical block of very shallow (<6 km deep) magnetic sources is spatially collocated with the Lupa

253 Fault. This zone of Lupa Fault-related shallow sources separates the CSZ-related sources from
254 another sub-vertical cluster of moderately deeper (~9 km-deep) magnetic sources that are spatially
255 collocated with the Katuma Terrane (Figs. 3B-D).

256

257 *The CSZ and the Early-rift (Karoo) Structure*

258 The Karoo-age basin of the Rukwa Rift widens southeastwards from c. 16 km to c. 57 km at the
259 terminus of the CSZ magnetic lineament, before narrowing to <16 km towards the southeast (Fig.
260 2B). The Karoo intra-basinal faults (KIF, $329^{\circ}\pm 9.6$; Fig. 2Bi) are dominated by a fault cluster,
261 spaced 4-6 km apart and striking oblique to the Lupa Fault (311°). The fault cluster is collocated
262 with the CSZ magnetic lineament and trends parallel to the lineament (Fig. 4A-B). Although, some
263 of the KIF faults dip to the SW, most of them dip to the NE (Fig. 2B). A Karoo isopach map shows
264 that the thickest sections (>1 km-thick) of the Karoo-age units are generally confined to the
265 northeast of the CSZ anomaly (yellow polygon in Fig. 2B; also see Figs. 2C-D). Adjacent to the
266 Katuma Terrane and CSZ lineament (i.e., northwestern half of the rift), the Lupa Fault has a
267 relatively high dip (~ 69°); this decreases south-eastwards to < 40° (Fig. 4C). Also, within the rift,
268 prominent basement ridges cluster along the CSZ, some of which appear to be fault-bounded (Fig.
269 2B). We note the strong alignment between the CSZ mean trend (326°), KIF mean trend
270 ($329^{\circ}\pm 9.6$), and that of all (Permian to Quaternary) rift faults (ARF, 330° ; Fig. 2Bii).

271

272 *Strain Distribution within the Rukwa Rift during Karoo Extension*

273 In the northwestern half of the Rukwa Rift, the proportion of Karoo-phase tectonic extension
274 accommodated by the KIF increased southeastwards from ~12 % to 64 % (Figs. 4C-D). This trend
275 is coincident with an increase in across-strike separation between the Lupa border fault and the
276 CSZ, from <10 km in the NW to ~30 km at the SE terminus of CSZ magnetic lineament (Fig. 4C;
277 see also Fig. 4A). However, southeastward from the CSZ terminus to the southeast tip of the basin,
278 total extension was largely accommodated by the Lupa Fault (up to 83 %; Fig. 4C). Also, NW of
279 the CSZ terminus, the curve for intra-basinal fault absolute extension tracks that of the total
280 absolute extension, whereas SE of the CSZ terminus, total absolute extension curve is not tracked
281 by that of the intra-basinal fault, rather, it is tracked by the Lupa Fault absolute extension (Fig.
282 4C). The southeastward increase in the percentage of total extension accommodated by the Lupa
283 Fault is consistent with the southeastward increase in the magnitude of Lupa Fault's offset of the
284 Top-Basement which shows a more pronounced increase just southeast of the CSZ terminus (see
285 'Lupa Fault offset of Top-Basement' curve in Fig. 4C). Northwest of the CSZ terminus, Lupa
286 Fault's offset of the Top-Basement shows a range of 2 - 6.4 km over a distance of 120 km, whereas
287 SE of the CSZ terminus, the basement offset increases from ~5.5 km to >9 km within ~20 km
288 distance.

289

290 **CONTROLS OF THE CSZ AND TERRANE BOUNDARY ON EARLY-RIFT** 291 **FAULTING, STRAIN DISTRIBUTION, AND BASIN ARCHITECTURE**

292 *Border Fault Development:*

293 The geometrical and spatial relationships between the Karoo rift-related structures, the CSZ, and
294 the adjacent basement terrane boundaries reveal how strain was localized and spatially partitioned

295 during the early phases of extension in the Rukwa Rift. The Lupa Fault is the largest rift-related
296 structure in the Rukwa Rift, having formed at the very onset of rifting, thus representing the border
297 fault (e.g., Morley et al., 1992, 1999; Kilembe and Rosendahl, 1992; Wheeler and Karson 1994).
298 Studies suggest that the Lupa Fault localized along terrane boundaries (Katuma-Wakole boundary
299 in the NW and Lupa-Mbozi boundary in the SE) and that its NW-SE trend is influenced by the
300 structural fabrics in the bounding Katuma Terrane (Figs. 1B, 3B-D; Daly, 1988; Wheeler and
301 Karson, 1994; Theunissen et al., 1996; Lemna et al., 2019; Heilman et al., 2019). However, the
302 observations supporting these hypotheses were based on the shallow geometries of structures
303 observed in the field or the plan-view structural trends of metamorphic fabrics expressed in
304 aeromagnetic data.

305 The sub-vertical dips described by the cluster of magnetic sources beneath the Katuma Terrane
306 (Figs. 3B) supports previous studies that argue that the Katuma-Wakole terrane boundary, and
307 fabrics within the Katuma Terrane, are steeply dipping. However, the Lupa Fault itself shows an
308 abrupt and significant decrease in dip just southeast of the Katuma Terrane termination (Fig. 4C),
309 where it is coincident with the E-W-trending Usagaran Belt and Lupa Terrane (Fig. 5A). Therefore,
310 we suggest that both the Katuma-Wakole Terrane boundary and the tectonic structures in the
311 Katuma Terrane are responsible for the steep dip of the Lupa border fault in the NW; in contrast,
312 to the SE, the absence of favorably oriented intra-basement structures result in the fault having a
313 lower dip.

314 The sub-vertical dip of the CSZ-related magnetic sources and southwest dip direction of the Lupa
315 Fault (Fig. 3C) also suggests that the deepest sections of the border fault could merge with the
316 shear zone at the deeper crustal levels, although it would require a southwestward dip for the CSZ
317 at depth. If this spatial and potentially kinematic relationship is true, we infer a depth-dependent

318 partitioning of the control of structural inheritance on the early development of the Lupa border
319 fault, such that the upper sections of the fault exploited the Katuma-Wakole Terrane boundary and
320 structures in the Katuma Terrane, and the deepest section exploited the Chisi Shear Zone.

321

322 *Intra-Basinal Faulting:*

323 The collocation and parallel trends of the KIF and CSZ suggest that the CSZ largely controlled the
324 localization of the Karoo intra-basinal faulting (Fig. 4A and 5A). The prominence of NE-dip
325 direction of the KIF faults (Fig. 4A) suggests that the KIF exploited the NE-dipping metamorphic
326 fabrics along the CSZ (Fig. 2A). The confinement of the main Karoo-age rift fill between the Lupa
327 Fault and CSZ (where present) (Fig. 5A) indicates that the KIF cluster directly influenced the first-
328 order sediment distribution during the early phases of extension. The Karoo-age basin is widest in
329 the northwest where the CSZ is present (CSZ rotates from NW to NNW trend, away from the Lupa
330 Fault), further indicating the influence of the CSZ and its geometry on the extent of the early rift-
331 related depocenter (Fig. 4A). The apparent confinement of earliest rift-related sediments also
332 provides further age constraints on the timing of formation of the intra-basinal fault cluster.
333 Overall, these observations indicate that the shear zone and terrane boundary represent discrete
334 zones of inherited mechanical weakness in the crust where brittle deformation was accommodated
335 during the early stages of continental extension.

336

337 *Early-Rift Paleotopography:*

338 The Karoo-age rift topography is likely dominated by the footwall uplift along the Lupa border
339 fault in the northeastern basin margin (Van der Beek et al., 1998; Morley et al., 1999). However,
340 the clustering of basement ridges along the submarine part of the CSZ, likely representative of
341 early syn-rift erosionally-resistant topography, is consistent with observations of topographic
342 ridges along the CSZ onshore (Figs. 1B and S2A). Elsewhere, prominent, erosionally-resistant
343 topographic ridges define the surface expression of the Mughese Shear Zone (Kolawole et al.,
344 2018), which appears to be a southeast continuation of the CSZ trend in the Karonga Basin (Fig.
345 1B). Such ridges represent elevated topographic domains that may represent important sediment
346 sources (e.g., Gawthorpe and Leeder, 2000). Thus, the chain of ridges along the CSZ represents
347 intra-basinal sediment-source regions near the southwestern basin margin, indicating an additional
348 importance of the CSZ during initial sedimentation in the Rukwa Rift.

349

350 *Early-Rift Distribution of Extension:*

351 Our analyses show that within the northwestern section of the basin, Karoo-age tectonic extension
352 was largely accommodated on both the CSZ-related intra-basinal faults (KIF) and the Lupa border
353 fault (Figs. 4C-D); in fact, during this initial phase of extension, more strain was accommodated
354 on intra-basinal faults than the (developing) border fault. In contrast, southeast of the CSZ
355 termination beneath the basin (or at significantly large separation distance), extension was
356 primarily accommodated along the Lupa border fault. These suggest that during the early phase of
357 rifting, there was a competition for extensional strain localization between the CSZ and the
358 Katuma-Wakole terrane boundary in the northwest. Due to the southward increase in separation
359 between the CSZ and Katuma-Wakole/Lupa-Mbozi terrane boundaries, and the absence of CSZ

360 in the southeastern section of the Karoo-age basin, tectonic extension was then primarily
361 accommodated along the Lupa Fault, which ultimately exploited the Lupa-Mbozi terrane boundary
362 (Fig. 4C-D). The significant increase in the Lupa Fault Top-basement offset just south of the CSZ
363 termination (Fig. 4C) also supports the dominant localization of extensional strain on the border
364 fault in the southeastern section of the basin where the CSZ-related KIF is absent. Thus, we suggest
365 that the CSZ strongly controlled the early-phase distribution of tectonic extension along the Rukwa
366 Rift.

367 This along-rift partitioning of strain resulted in a lateral change of the overall Karoo-age rift
368 geometry from a shallower graben in the northwest, to a deep half graben in the southeast. This
369 along-rift change in rift geometry was previously thought to be primarily related to variation in
370 border fault strain accommodation controlled by oblique extensional kinematics (Morley et al.,
371 1992). Also, the obliquity of the intra-basinal faults relative to the border fault trend (Figs. 4B and
372 5B) has been used as a basis for inferring pull-apart and oblique extension kinematics for the rift
373 development (Kilembe and Rosendahl, 1992; Chattopadhyay & Chakra, 2013). However, detailed
374 structural interpretation from seismic reflection data revealed a minor component of strike-slip-
375 related deformation along the rift (Morley et al., 1999). Thus, we here suggest that the observed
376 obliquity of intra-basinal faults to border fault trend is primarily controlled by the focusing of
377 extensional strain along prominent pre-existing discrete zones of basement weakness during the
378 early phase of rifting. The geometrical alignment of the intra-basinal faults to the CSZ trend could
379 have been influenced by local stress rotation (SHmax) into CSZ-parallel/sub-parallel trend during
380 the early rift phase; a mechanism that has been proposed to explain the influence of weak basement
381 fabrics on the present-day orthogonal extension kinematics along the Rukwa Rift (Morley, 2010).
382 This resolves a long-standing controversy related to the geometrical structure and kinematics of

383 rift faulting in the Rukwa Rift. Elsewhere along the Rukwa Trend, farther northwest of the Rukwa
384 Rift, the Busindi border fault of the Luama Rift exploited the NW continuation of the CSZ (Figs.
385 1B and 3D), demonstrating the broader influence of the CSZ on the development of the other
386 Karoo rift segments of the Rukwa Trend. In the Tanganyika Rift, the along-rift distribution of
387 tectonic extension is influenced by the lateral variation of the inherited crustal rheology (Wright
388 et al., 2020), further demonstrating the strong influence of structural inheritance on the early
389 localization and distribution of extension along continental rifts.

390

391 *Post-Karoo Rift Architecture:*

392 Geological and geophysical evidence for post-Karoo strike-slip deformation has been recorded
393 along the Rukwa Rift (Wheeler and Karson, 1994; Delvaux et al., 2012; Heilman et al., 2019),
394 possibly associated with a plate-scale compressional event (Daly et al., 1991; Delvaux et al., 2021).
395 However, the analyses of seismic reflection profiles across the Rukwa Rift show that post-Karoo
396 strike-slip or compressional deformation in the basin was very minor (Morley et al., 1999).
397 Therefore, it is not likely that the plate-scale compressional event significantly altered the karoo-
398 age fault patterns in the Rukwa Rift.

399 The CSZ and adjacent terrane boundaries continued and still continue to influence rift geometry
400 long after the Karoo phase of extension. First, the mean trend of the rift faults, all combined
401 (Permian to Quaternary), generally remains the same as the Karoo-age mean intra-basinal fault
402 trend (Figs. 2Bi-ii; Morley et al., 1992; Kilembe and Rosendahl, 1992). Second, the along-strike
403 projection of the CSZ southeast of its magnetic anomaly termination is coincident with location
404 and orientation of the Msongano Trough, which represents a southeastward continuation of the

405 Rukwa Rift during the Cenozoic rifting phase (Fig. 5A). We suggest that the extension of the KIF
406 to the CSZ termination zone already established the incipient graben of the Msongano Trough
407 during the Karoo rifting phase (Figs. 5A and 6). We suggest that the CSZ and its colinear Mughese
408 Shear Zone, along which the Msongano Trough developed (Fig. 5A), both constitute coupled
409 discrete zones of weakness in the basement that accommodated the continuous lateral
410 southeastward propagation of the KIF as a narrow graben during the post-Karoo phases of
411 extension. Thus, the present-day bifurcation of the Rukwa Rift into the Songwe and Msongano
412 troughs (Fig. 1C) was established during the very earliest stage of rifting. In addition, the
413 southeastern border fault of the Rukwa Rift (Ufipa Fault; Fig. 2B) which developed in the
414 Cenozoic, largely exploited the tectonic fabrics of the Ufipa Terrane (Heilman et al., 2019).

415 More broadly, in the Cenozoic Tanganyika Rift, located northwest of the Rukwa Rift (Figs. 1A-
416 B), the rift basin is segmented (Sander and Rosendahl, 1989; Muirhead et al., 2019; Wright et al.,
417 2020). The segmentation occurs at the proposed splay of the CSZ magnetic lineaments (Fig. 1B).
418 The Ruzizi and East Kigoma sub-basins are separated by the northern section of the East CSZ
419 splay, whereas the East and West Kigoma sub-basins are separated by the southern section of the
420 East Splay, and the West Kigoma and Kalemie Sub-basins are separated by the CSZ segment
421 extending into the Luama Rift. In essence, not only did the CSZ influence the early-phase
422 architecture of the Karoo-age Rukwa and Luama rift basins, but also the structure of the relatively
423 younger Tanganyika Rift. The spatial collocation of Cenozoic hydrothermal vents within different
424 sections of the CSZ in the Tanganyika Rift (diamond symbols in Fig. 1B) highlights the deep
425 reaches of the rift faults that exploited the basement weakness of the shear zone.

426

427 **IMPLICATIONS FOR EARLY-STAGE ARCHITECTURE OF CONTINENTAL RIFT**
428 **BASINS**

429 Our study of the Rukwa Rift suggests that early-phase rift strain is significantly accommodated by
430 intra-basinal faults, contrary to observations in some other juvenile magma-poor continental rifts
431 (e.g., Nixon et al., 2016; Muirhead et al., 2019), but it is localized onto pre-existing structures. The
432 early-phase strain localization in the Rukwa Rift occurred via two different styles with associated
433 deformational mechanisms. One style (Style-1 strain localization) is the localization of a large rift
434 fault onto a narrow discrete zone of basement weakness, such as prominent basement terrane
435 boundaries (this study), pre-existing fault zones, and narrow ductile shear zones, in which case the
436 structures of the weak zone and the fabrics of the adjacent basement may influence the fault
437 geometry (Fig. 6). An example of this is the development of the Livingstone Fault in the Karonga
438 Basin, northern Malawi Rift (Wheeler and Karson, 1989), the Thyolo border fault in the Shire Rift
439 Zone (Wedmore et al., 2020b), and splay faulting at a terrane boundary during the Late Cretaceous
440 extension between Zealandia and Australia (Phillips and McCaffrey, 2019b). A second style
441 (Style-2 strain localization) is the localization of a fault cluster (or fault belt) onto a broader discrete
442 zone of basement weakness, such as wide pre-rift shear zones or subduction suture zones (this
443 study), in which case the individual fault strands may exploit the smaller-scale mechanical
444 heterogeneities within the broad zone of basement weakness (Fig. 6). An example of Style-2
445 localization is the development of a fault cluster along the western margin of the Karonga Basin,
446 northern Malawi Rift, where the fault cluster exploited the >15 km-wide Precambrian Mughese
447 Shear Zone (Kolawole et al., 2018). Therefore, we hypothesize that during the earliest stages of
448 continental rifting, strain initially localizes on pre-existing zones of crustal weakness, and the style
449 of localization may be associated with the type of the inheritance and character of the inherited

450 structure. In addition, we note that whilst pre-existing structure may exert a strong control on strain
451 distribution and localization during the earliest phase of continental extension, the established early
452 rift template, may persist through the subsequent phases of the stretching stage of rifting (i.e., prior
453 to the necking and hyper-extension stages).

454

455 **CONCLUSIONS**

456 We investigated the distribution of strain during the earliest phase of extension in the Rukwa Rift,
457 a Phanerozoic multiphase magma-poor rift basin that developed along the trend of the Precambrian
458 Chisi Shear Zone (CSZ) and terrane boundary shear zones in East Africa.

459 Here are our main findings:

460 1) During the earliest phase of extension, although the border fault, Lupa Fault exploited the
461 colinear Katuma-Wakole and Lupa-Mbozi terrane boundaries, the CSZ facilitated the early
462 localization and development of a prominent intra-basinal fault cluster.

463 2) In the northwestern section of the rift, the presence and proximity of the CSZ and the Katuma-
464 Wakole terrane boundary facilitated a competition for strain localization between the CSZ and the
465 adjacent terrane boundary, whereas in the southeastern section where the CSZ is either absent or
466 at a significantly large distance, strain is primarily localized along the Lupa-Mbozi terrane
467 boundary.

468 3) The along-rift variation in early phase rift geometry, rift margin paleotopography, and
469 depocenter extents were largely controlled by the CSZ.

470 4) The along-rift distribution of early-phase extension was largely influenced by structural
471 inheritance, such that in the northwestern section of the rift, significant extension is accommodated

472 by the intra-basinal fault cluster that exploited the CSZ, whereas in the southeast, extension is
473 largely accommodated by the Lupa border fault.

474 5) Two styles of early-phase strain localization in which a.) strain is localized onto a narrow
475 discrete zone of basement weakness in the form of a large rift fault (Style-1 strain localization),
476 and b.) strain is localized onto a broad discrete zone of basement weakness in the form of a fault
477 cluster (Style-2 strain localization).

478 6) Whilst pre-existing basement structure may exert the strong control on strain distribution and
479 localization during the earliest phase of extension, the established early rift template, may persist
480 through the subsequent phases of the stretching stage of rifting.

481 Our findings offer a window into the early stages of continental extension along a young evolving
482 magma-poor rift, where early strain is not accommodated only by border the fault as suggested by
483 existing magma-poor early-rift models; instead, strain focuses relatively quickly on a large border
484 fault and intra-basinal fault clusters that follow pre-existing intra-basement structures. This study
485 reveals the influence of structural inheritance on early-phase rift geometry and along-rift
486 partitioning of strain along magma-poor rift basins.

487

488 **ACKNOWLEDGMENTS**

489 We thank two anonymous reviewers for their insightful comments that have helped to improve
490 the quality of our paper, and we also thank the editor, James Muirhead for handling our paper.

491 We thank Obeid Lemna for providing useful comments on the preprint of the initial version of
492 the manuscript uploaded on EarthArXiv. We thank the South African Council for Geoscience for
493 providing the aeromagnetic data to EA used in this study. The aeromagnetic data is archived at
494 <http://sadc-gla.org/SADC/home.html>. We have provided uninterpreted versions of the

495 aeromagnetic data in our supplementary document. The seismic reflection cross-section of the
496 Rukwa Rift shown in this study (Fig. 2C) and other 2-D seismic datasets from the basin are
497 archived in the appendix of Morley et al. (1999).

498

499 **CONFLICTS OF INTEREST STATEMENT**

500 Author Folarin Kolawole is currently employed by BP America. However, this study and the
501 initial manuscript drafts were developed and completed during his stay at the University of
502 Oklahoma, prior to joining BP. The remaining authors declare that the research was conducted in
503 the absence of any commercial or financial relationships that could be construed as a potential
504 conflict of interest.

505

506 **REFERENCES CITED**

- 507 Agostini, A., Bonini, M., Corti, G., Sani, F. and Mazzarini, F., 2011. Fault architecture in the Main
508 Ethiopian Rift and comparison with experimental models: implications for rift evolution and
509 Nubia–Somalia kinematics. *Earth and Planetary Science Letters*, 301(3-4), 479-492.
- 510 Baranov, V. (1957). A new method for interpretation of aeromagnetic maps: Pseudo-gravimetric
511 anomalies. *Geophysics*, 22(2), 359–382.
- 512 Boniface, N. and Schenk, V., 2012. Neoproterozoic eclogites in the Paleoproterozoic Ubendian
513 belt of Tanzania: Evidence for a Pan-African suture between the Bangweulu block and the
514 Tanzania craton. *Precambrian Research*, 208, 72-89.
- 515 Boniface, N., Schenk, V. and Appel, P., 2012. Paleoproterozoic eclogites of MORB-type
516 chemistry and three Proterozoic orogenic cycles in the Ubendian Belt (Tanzania): Evidence from
517 monazite and zircon geochronology, and geochemistry. *Precambrian Research*, 192, 16-33.
- 518 Boven, A., Theunissen, K., Sklyarov, E., Klerkx, J., Melnikov, A., Mruma, A. and Punzalan, L.,
519 1999. Timing of exhumation of a high-pressure mafic granulite terrane of the Paleoproterozoic
520 Ubende belt (West Tanzania). *Precambrian Research*, 93(1), 119-137.
- 521 Buiter, S.J.H., Torsvik, T.H., 2014. A review of Wilson Cycle plate margins: a role for mantle
522 plumes in continental break-up along sutures? *Gondwana Research* 26, 627–653.
- 523 Chattopadhyay, A. and Chakra, M., 2013. Influence of pre-existing pervasive fabrics on fault
524 patterns during orthogonal and oblique rifting: an experimental approach. *Marine and Petroleum*
525 *Geology*, 39(1), pp.74-91.
- 526 Chorowicz, J., 2005. The east African rift system. *Journal of African Earth Sciences*, 43(1-3), 379-
527 410.
- 528 Christian Schiffer, Anthony G. Doré, Gillian R. Foulger, Dieter Franke, Laurent Geoffroy, Laurent
529 Gernigon, Bob Holdsworth, Nick Kusznir, Erik Lundin, Ken McCaffrey, Alexander L. Peace,
530 Kenni D. Petersen, Thomas B. Phillips, Randell Stephenson, Martyn S. Stoker, J. Kim Welford
531 (2019) Structural inheritance in the North Atlantic. *Earth-Science Reviews*.
- 532 Claringbould, J. S., Bell, R., Jackson, C. A., Gawthorpe, R., & Odinsen, T. (2019). Complex strain
533 partitioning and heterogeneous extension rates during early rifting in the East Shetland Basin,
534 northern North Sea. *EarthArxiv*. <https://doi.org/10.31223/osf.io/nbe2c>
- 535 Daly, M. C. (1988). Crustal shear zones in central Africa—A kinematic approach to Proterozoic
536 tectonics. *Episodes*, 11(1), 5–11.
- 537 Daly, M. C., Chorowicz, J., & Fairhead, J. D. (1989). Rift basin evolution in Africa: The influence
538 of reactivated steep basement shear zones. *Geological Society, London, Special Publications*,
539 44(1), 309–334.

- 540 Daly, M.C., Lawrence, S.R., Kimun'a, D. and Binga, M. (1991). Late Palaeozoic deformation in
541 central Africa: a result of distant collision?. *Nature*, 350(6319), pp.605-607.
- 542 Delvaux, D., 2001. Karoo rifting in western Tanzania: Precursor of Gondwana breakup.
543 Contributions to geology and paleontology of Gondwana in honor of Helmut Wopfner: Cologne,
544 Geological Institute, University of Cologne, 111-125.
- 545 Delvaux, D., Kervyn, F., Macheyeke, A. S., & Temu, E. B. (2012). Geodynamic significance of
546 the TRM segment in the East African Rift (W-Tanzania): Active tectonics and paleostress in the
547 Ufipa plateau and Rukwa basin. *Journal of Structural Geology*, 37, 161–180.
- 548 Delvaux, D., Maddaloni, F., Tesauero, M. and Braitenberg, C. (2021). The Congo Basin:
549 Stratigraphy and subsurface structure defined by regional seismic reflection, refraction and well
550 data. *Global and Planetary Change*, 198, p.103407.
- 551 Dewey, J., Spall, H., 1975. Pre-Mesozoic plate tectonics: how far back in Earth history can the
552 Wilson Cycle be extended? *Geology* 3, 422–424.
- 553 Ebinger, C., 2005. Continental break-up: the East African perspective. *Astronomy & Geophysics*,
554 46(2), pp.2-16.
- 555 Ganbat, A., Tsujimori, T., Boniface, N., Pastor-Galán, D., Aoki, S. and Aoki, K., 2021. Crustal
556 evolution of the Paleoproterozoic Ubendian Belt (SW Tanzania) western margin: A Central
557 African Shield amalgamation tale. *Gondwana Research*, 91, pp.286-306.
- 558 Gawthorpe, R.L. and Leeder, M.R., 2008. Tectono-sedimentary evolution of active extensional
559 basins. *Basin Research*, 12(3-4), pp.195-218.
- 560 Hayward, N.J. and Ebinger, C.J., 1996. Variations in the along-axis segmentation of the Afar Rift
561 system. *Tectonics*, 15(2), pp.244-257.
- 562 Heilman, E., Kolawole, F., Atekwana, E. A. and Mayle, M., 2019. Controls of Basement Fabric
563 on the Linkage of Rift Segments. *Tectonics*, 38(4), pp.1337-1366.
- 564 Hodgson, I., Illsley-Kemp, F., Gallacher, R.J., Keir, D., Ebinger, C.J. and Mtelega, K., 2017.
565 Crustal structure at a young continental rift: A receiver function study from the Tanganyika Rift.
566 *Tectonics*, 36(12), pp.2806-2822.
- 567 Kilembe, E.A. and Rosendahl, B.R., 1992. Structure and stratigraphy of the Rukwa rift. In: C.J.
568 Ebinger, H.K. Gupta and I.O. Nyambok (Editors), *Seismology and Related Sciences in Africa*.
569 *Tectonophysics*, 209: 143-158.s
- 570 Klerkx, J., Theunissen, K. and Delvaux, D., 1998. Persistent fault controlled basin formation since
571 the Proterozoic along the Western Branch of the East African Rift. *Journal of African Earth
572 Sciences*, 26(3), pp.347-361.
- 573 Kolawole, F., Atekwana, E.A., Laó-Dávila, D.A., Abdelsalam, M.G., Chindandali, P.R., Salima,
574 J. and Kalindekaffe, L., 2018. Active deformation of Malawi rift's north basin Hinge zone

575 modulated by reactivation of preexisting Precambrian Shear zone fabric. *Tectonics*, 37(3), 683-
576 704.

577 Kolawole, F., Atekwana, E.A., Malloy, S., Stamps, D.S., Grandin, R., Abdelsalam, M.G., Leseane,
578 K. and Shemang, E.M., 2017. Aeromagnetic, gravity, and Differential Interferometric Synthetic
579 Aperture Radar analyses reveal the causative fault of the 3 April 2017 Mw 6.5 Moiyabana,
580 Botswana, earthquake. *Geophysical Research Letters*, 44(17), pp.8837-8846.

581 Lee, H., Fischer, T.P., Muirhead, J.D., Ebinger, C.J., Kattenhorn, S.A., Sharp, Z.D., Kianji, G.,
582 Takahataf, N., Sano, Y., 2017. Incipient rifting accompanied by the release of subcontinental
583 lithospheric mantle volatiles in the Magadi and Natron basin, East Africa. *J. Volcanol. Geotherm.*
584 *Res.*346, 118–133.

585 Lemna, O.S., Stephenson, R. and Cornwell, D.G., 2019. The role of pre-existing Precambrian
586 structures in the development of Rukwa Rift Basin, southwest Tanzania. *Journal of African Earth*
587 *Sciences*, 150, 607-625.

588 Lenoir, J.L., Liégeois, J.P., Theunissen, K. and Klerkx, J., 1994. The Palaeoproterozoic Ubendian
589 shear belt in Tanzania: geochronology and structure. *Journal of African Earth Sciences*, 19(3),
590 pp.169-184.

591 Muirhead, J.D., Kattenhorn, S.A., Lee, H., Mana, S., Turrin, B.D., Fischer, T.P., Kianji, G., Dindi,
592 E., Stamps, D.S., 2016. Evolution of upper crustal faulting assisted by magmatic volatile release
593 during early-stage continental rift development in the East African Rift. *Geosphere*, 12, 1670–
594 1700.

595 Muirhead, J.D., Wright, L.J. and Scholz, C.A., 2019. Rift evolution in regions of low magma input
596 in East Africa. *Earth and Planetary Science Letters*, 506, pp.332-346.

597 Morley, C.K., 2010. Stress re-orientation along zones of weak fabrics in rifts: An explanation for
598 pure extension in ‘oblique’ rift segments?. *Earth and Planetary Science Letters*, 297(3-4), pp.667-
599 673.

600 Morley, C.K., Cunningham, S.M., Harper, R.M. and Wescott, W.A., 1992. Geology and
601 geophysics of the Rukwa rift, East Africa. *Tectonics*, 11(1), pp.69-81.

602 Morley, C.K., Wescott, W.A., Harper, R.M. and Cunningham, S.M., 1999. Geology and
603 geophysics of the Rukwa Rift. *Geoscience of Rift Systems-Evolution of East Africa. AAPG*
604 *Studies in Geology*, 44, pp.91-110.

605 Naliboff, J.B., Buitter, S.J., Péron-Pinvidic, G., Osmundsen, P.T. and Tetreault, J., 2017. Complex
606 fault interaction controls continental rifting. *Nature communications*, 8(1), pp.1-9.

607 Nixon, C.W., McNeill, L.C., Bull, J.M., Bell, R.E., Gawthorpe, R.L., Henstock, T.J.,
608 Christodoulou, D., Ford, M., Taylor, B., Sakellariou, D. and Ferentinos, G., 2016. Rapid
609 spatiotemporal variations in rift structure during development of the Corinth Rift, central Greece.
610 *Tectonics*, 35(5), pp.1225-1248.

611 Osagiede, E.E., Rotevatn, A., Gawthorpe, R., Kristensen, T.B., Jackson, C.A. and Marsh, N., 2020.
612 Pre-existing intra-basement shear zones influence growth and geometry of non-colinear normal
613 faults, western Utsira High–Heimdal Terrace, North Sea. *Journal of Structural Geology*, 130,
614 p.103908.

615 Phillips, T.B., Fazlikhani, H., Gawthorpe, R.L., Fossen, H., Jackson, C.A.L., Bell, R.E., Faleide,
616 J.I. and Rotevatn, A., 2019a. The Influence of Structural Inheritance and Multiphase Extension on
617 Rift Development, the Northern North Sea. *Tectonics*, 38.

618 Phillips, T.B. and McCaffrey, K.J., 2019b. Terrane Boundary Reactivation, Barriers to Lateral
619 Fault Propagation and Reactivated Fabrics: Rifting Across the Median Batholith Zone, Great South
620 Basin, New Zealand. *Tectonics*, 38(11), 4027-4053.

621 Ragon, T., Nutz, A., Schuster, M., Ghienne, J.F., Ruffet, G. and Rubino, J.L., 2019. Evolution of
622 the northern Turkana Depression (East African Rift System, Kenya) during the Cenozoic rifting:
623 New insights from the Ekitale Basin (28-25.5 Ma). *Geological Journal*, 54(6), pp.3468-3488.

624 Roberts, E.M., O'Connor, P.M., Stevens, N.J., Gottfried, M.D., Jinnah, Z.A., Ngasala, S., Choh,
625 A.M. and Armstrong, R.A., 2010. Sedimentology and depositional environments of the Red
626 Sandstone Group, Rukwa Rift Basin, southwestern Tanzania: New insight into Cretaceous and
627 Paleogene terrestrial ecosystems and tectonics in sub-equatorial Africa. *Journal of African Earth
628 Sciences*, 57(3), pp.179-212.

629 Roberts, E.M., Stevens, N.J., O'Connor, P.M., Dirks, P.H.G.M., Gottfried, M.D., Clyde, W.C.,
630 Armstrong, R.A., Kemp, A.I.S. and Hemming, S., 2012. Initiation of the western branch of the
631 East African Rift coeval with the eastern branch. *Nature Geoscience*, 5(4), pp.289-294.

632 Salem, A., Williams, S., Fairhead, J. D., Smith, R., & Ravat, D. (2007). Interpretation of magnetic
633 data using tilt-angle derivatives. *Geophysics*, 73(1), L1–L10.

634 Sklyarov, E.V., Theunissen, K., Melnikov, A.I., Klerkx, J., Gladkochub, D.P., Mruma, A., 1998.
635 Paleoproterozoic eclogites and garnet pyroxenites of the Ubende Belt (Tanzania). *Schweizerische
636 Mineralogische Petrographische Mitteilungen* 78, 257–271.

637 Smirnov, V., Pentelkov, V., Tolochko, V., Trifan, M., Zhukov, S., 1973. Geology and minerals of
638 the central part of the western rift. Tech. rep., Mineral and Resource Division, Dodoma, Tanzania.
639 Unpublished report of the geological mapping.

640 Theunissen, K., Klerkx, J., Melnikov, A., & Mruma, A. (1996). Mechanisms of inheritance of rift
641 faulting in the western branch of the East African Rift, Tanzania. *Tectonics*, 15(4), 776–790.

642 Van der Beek, P., Mbede, E., Andriessen, P. and Delvaux, D., 1998. Denudation history of the
643 Malawi and Rukwa Rift flanks (East African Rift System) from apatite fission track
644 thermochronology. *Journal of African Earth Sciences*, 26(3), pp.363-385.

645 Versfelt, J.W. (2009), South Atlantic margin rift basin asymmetry and implications for pre-salt
646 exploration. International Petroleum Technology Conference (IPTC) paper 13833, Doha, Qatar.

647 Wang, L., Maestrelli, D., Corti, G., Zou, Y. and Shen, C., 2021. Normal fault reactivation during
648 multiphase extension: Analogue models and application to the Turkana depression, East Africa.
649 *Tectonophysics*, 811, p.228870.

650 Wedmore, L.N., Biggs, J., Williams, J.N., Fagereng, Å., Dulanya, Z., Mphepo, F. and Mdala, H.,
651 2020a. Active fault scarps in southern Malawi and their implications for the distribution of strain
652 in incipient continental rifts. *Tectonics*, 39(3), p.e2019TC005834.

653 Wedmore, L.N., Williams, J.N., Biggs, J., Fagereng, Å., Mphepo, F., Dulanya, Z., Willoughby, J.,
654 Mdala, H. and Adams, B.A., 2020b. Structural inheritance and border fault reactivation during
655 active early-stage rifting along the Thyolo fault, Malawi. *Journal of Structural Geology*, 139,
656 104097.

657 Wheeler, W.H. and Karson, J.A., 1989. Structure and kinematics of the Livingstone Mountains
658 border fault zone, Nyasa (Malawi) Rift, southwestern Tanzania. *Journal of African Earth Sciences*
659 (and the Middle East), 8(2-4), 393-413.

660 Wheeler, W.H. and Karson, J.A., 1994. Extension and subsidence adjacent to a "weak" continental
661 transform: An example from the Rukwa rift, East Africa. *Geology*, 22(7), 625-628.

662 Wilson, J.T., 1966. Did the Atlantic close and then re-open? *Nature* 211, 676–681.

663 Wright, L. J. M., Muirhead, J. D., & Scholz, C. A. (2020). Spatiotemporal variations in upper
664 crustal extension across the different basement terranes of the Lake Tanganyika Rift, East Africa.
665 *Tectonics*, 39, e2019TC006019.

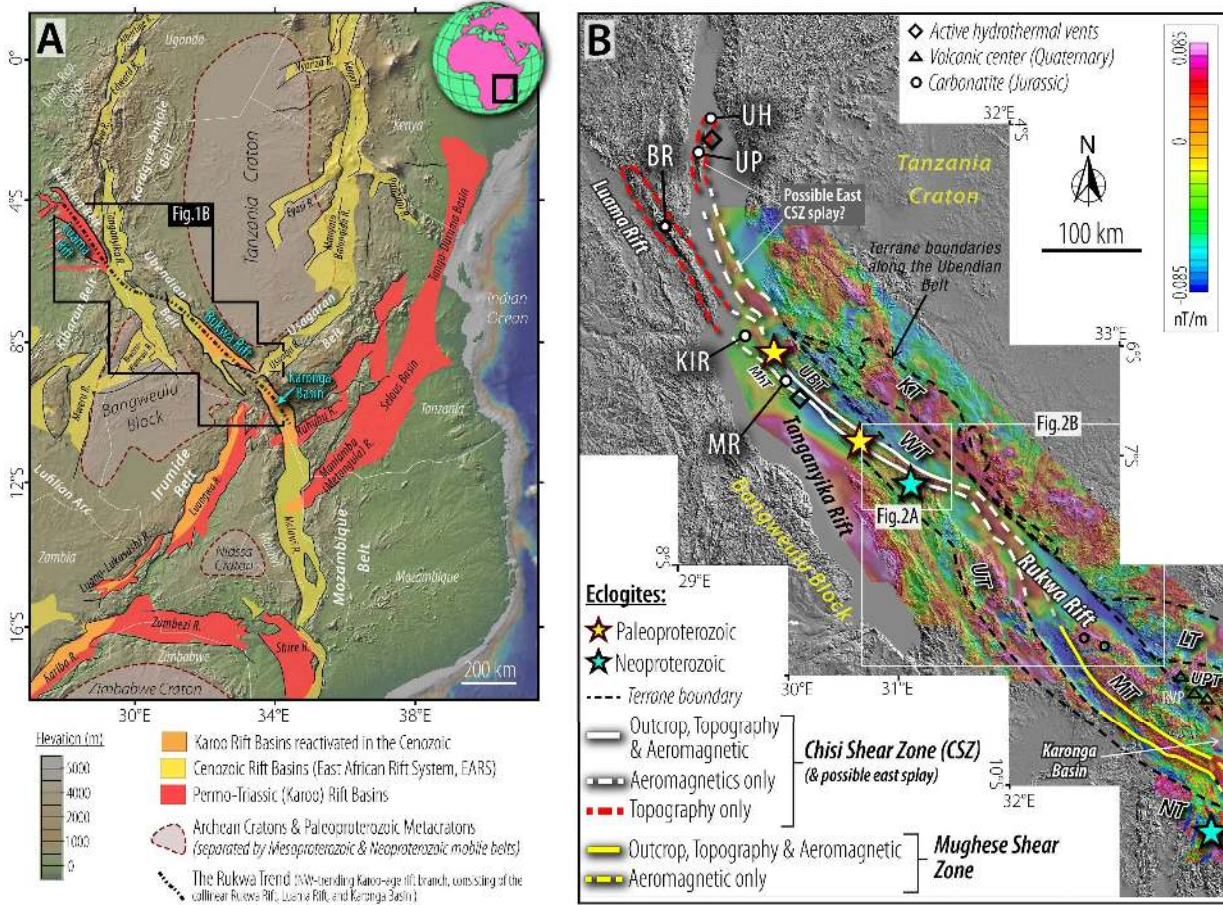
666

667

668

669

670



672

673 **Figure 1. A:** Map of east Africa showing the Permo-Triassic (i.e., Karoo rift system) rift segments,
 674 and the currently active rift segments (i.e., East African Rift System). **B:** Shuttle Radar
 675 Topography Mission (SRTM) Digital Elevation Model (DEM) hillshade covering the Rukwa Rift
 676 Trend, overlaid with the vertical derivative aeromagnetic of SW Tanzania. Black dashed lines
 677 represent boundaries of the Precambrian terranes of the Rukwa Rift Trend (after Daly, 1988;
 678 Lenoir et al., 1994; Delvaux et al., 2012; Lemna et al., 2018; Heilman et al., 2019). Locations of
 679 Proterozoic eclogites in the Ubendian Belt are from Boniface et al. (2012) and Boniface and
 680 Schenk (2012). Locations of hydrothermal vents and Mesozoic-Cenozoic igneous centers
 681 (volcanics and carbonatites) are obtained from Hodgson et al. (2017). See uninterpreted
 682 aeromagnetic and hillshade maps in supplementary figures 1 and 2. Geomorphic features: BR
 683 (Busindi Ridge), KIR (Kavala Island Ridge), MR (Mahale Ridge), UP (Ubwari Peninsula), UH
 684 (Ubwari Horst). Terranes of the Ubendian Belt: KT (Katuma Terrane), LT (Lupa Terrane), MT
 685 (Mbozi Terrane), MhT (Mahale Terrane), RVP (Rungwe Volcanic Province), UBT (Ubende
 686 Terrane), UPT (Upangwa Terrane), UT (Ufipa Terrane), WT (Wakole Terrane).

687

688

689
 690
 691
 692
 693
 694
 695
 696
 697
 698
 699
 700
 701
 702
 703
 704
 705
 706
 707
 708
 709
 710
 711
 712
 713
 714
 715
 716
 717
 718
 719
 720
 721

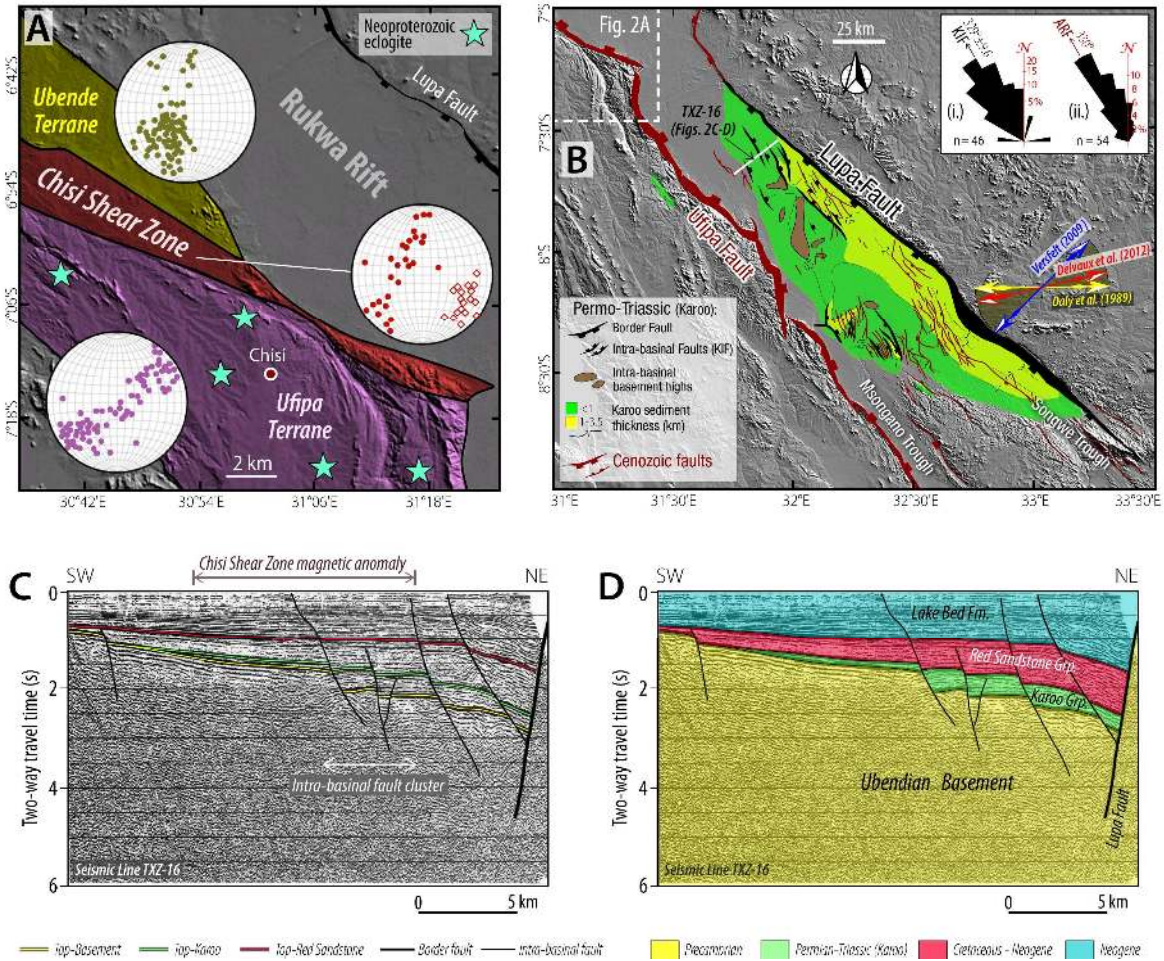
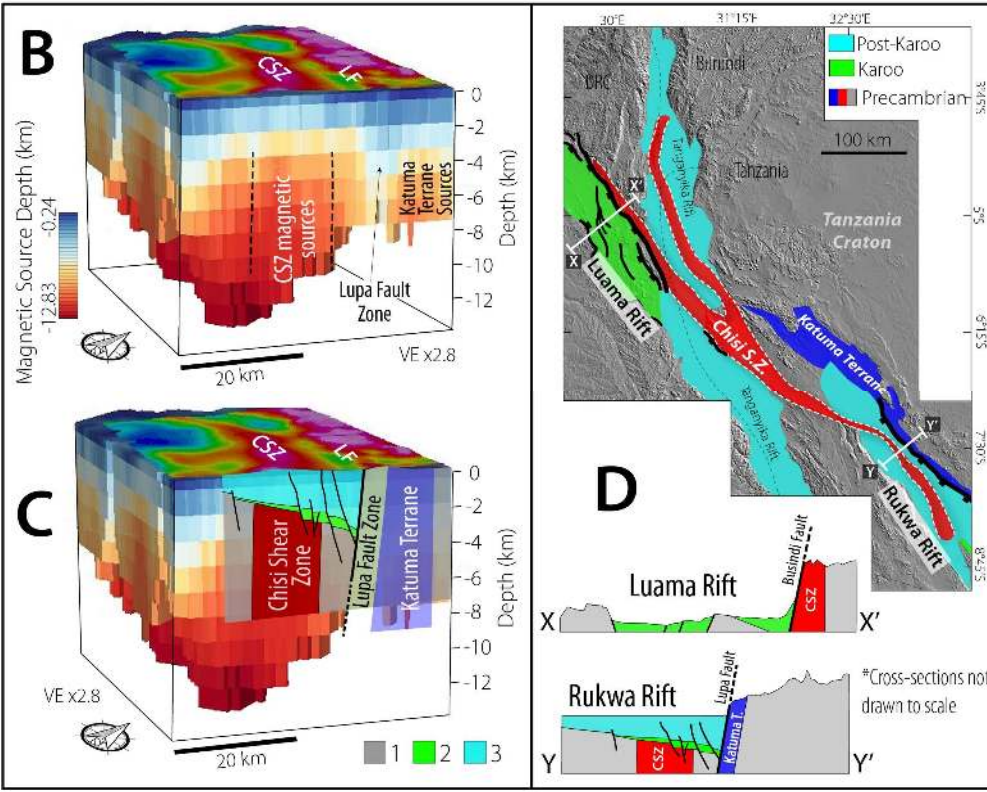
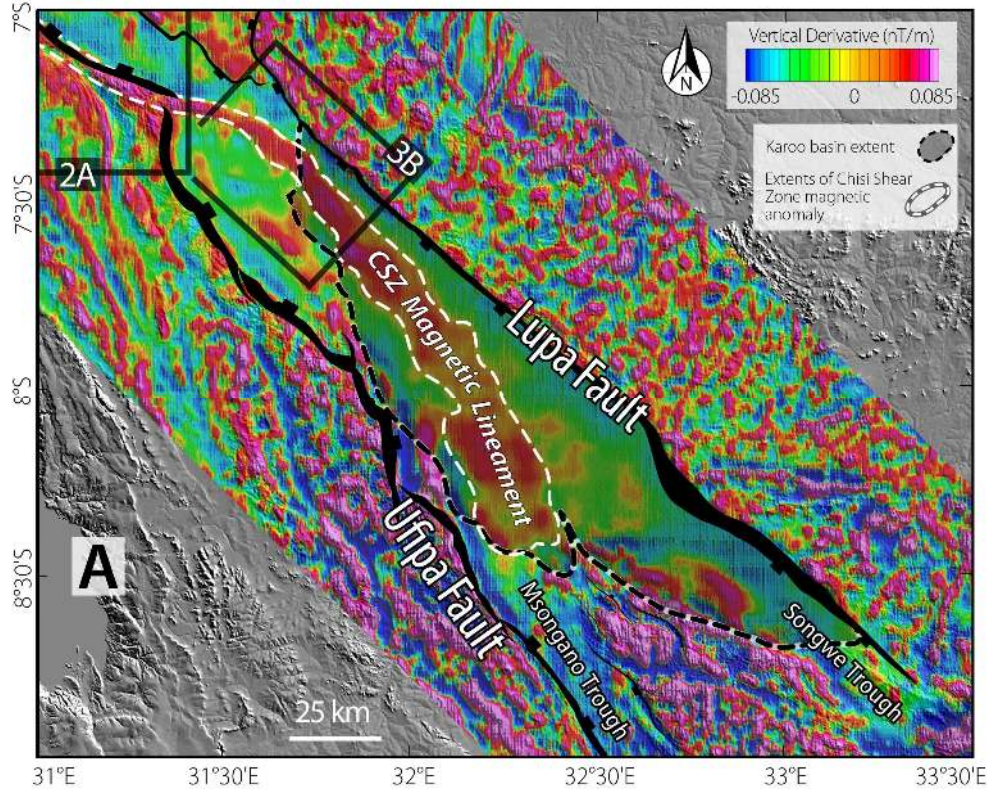


Figure 2. **A:** Satellite digital elevation model (DEM) hillshade of the NW Rukwa Rift shoulder (see Figs. 1B and 2B for location) showing the Precambrian Chisi Shear Zone exposure and its bounding basement terranes. The plots of equal area stereographic projection (lower hemisphere) show the poles to planes of gneissic foliation (filled circles), and poles of mineral elongation lineation and some fold axes of asymmetric intrafolial folds (diamonds in the Chisi Shear Zone stereonet) measured in field outcrops (from Boven et al., 1999). These structures represent the metamorphic basement fabrics of the basement. Locations of Neoproterozoic eclogites in the Chisi area are from Boniface and Schenk (2012). **B:** Map of the Rukwa Rift showing the interpreted Karoo and post-Karoo structural elements (structural elements are from Morley et al., 1992, 1999). Arrows represent the previously published inferred Karoo extension directions. *Inset:* Frequency-azimuth distribution plot for (i.) Karoo-age (Permo-Triassic) intra-basinal faults (KIF) with black arrow indicating their mean trend and standard error (measured in this study), and (ii.) All (Permian to Quaternary) Rukwa Rift faults (ARF) with their mean trend shown as brown arrow (digitized from Morley et al., 1992). **C - D:** 2-D seismic reflection profile line TXZ-16 and interpretation (modified from Morley et al., 1999; see location in Fig. 2B) showing the major stratigraphic boundary horizons, the Lupa border fault, and intra-basinal faults.

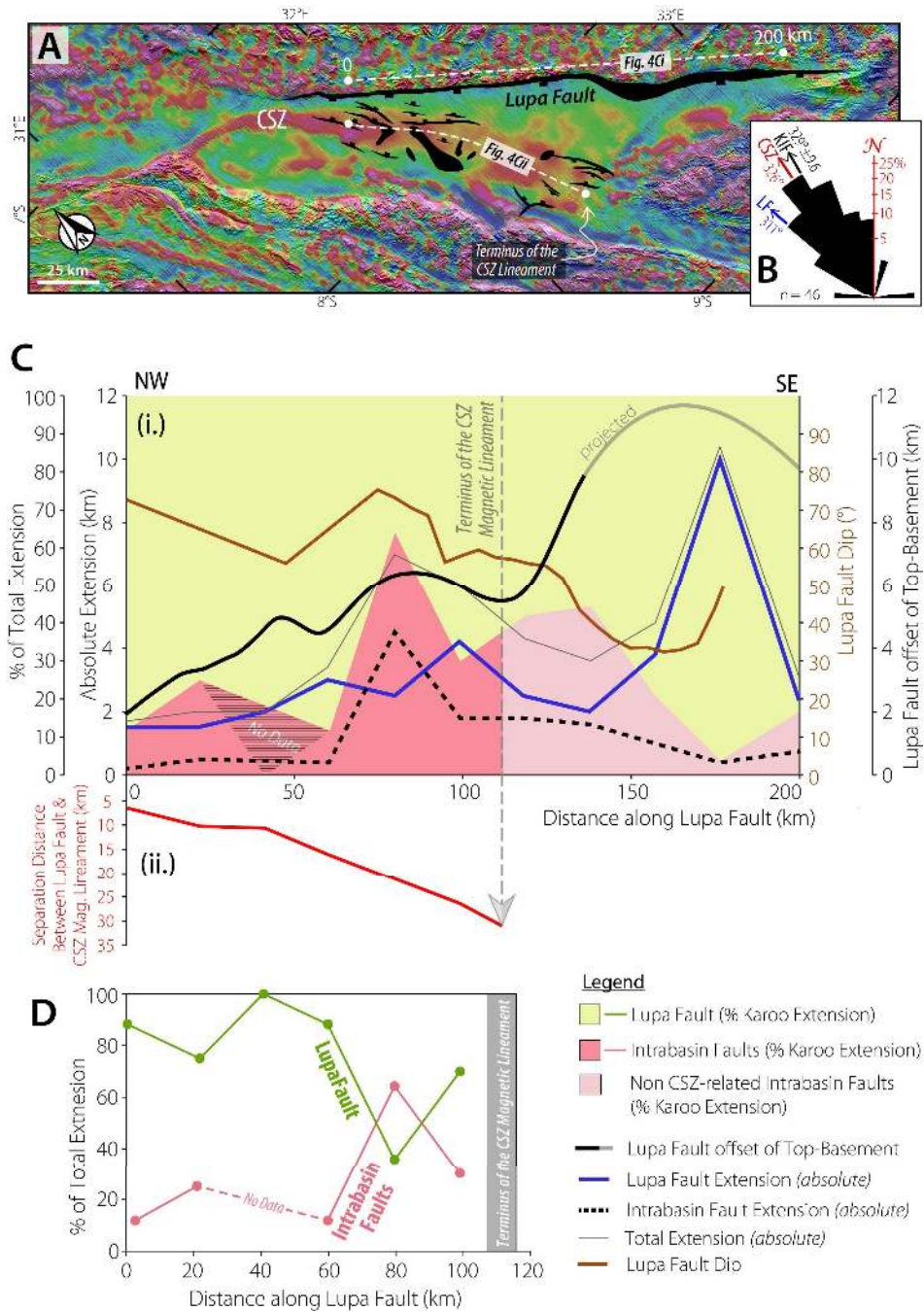
722
723
724
725
726
727
728
729
730
731
732
733
734
735
736
737
738
739
740
741
742
743
744
745
746
747
748
749
750



751 **Figure 3. A:** Vertical derivative of the aeromagnetic grid overlaid on satellite Digital Elevation
752 Model (DEM) hillshade, showing the rift border faults, rift shoulder basement fabrics and the
753 aeromagnetic signature of the Chisi Shear Zone (CSZ) along the rift axis. See uninterpreted
754 aeromagnetic maps in supplementary figure 1. **B:** 3-D gridded block of the Source Parameter
755 Imaging (SPI) solutions from the transform of the aeromagnetic grid, showing the subsurface
756 extents and geometry of CSZ and the shallower Katuma Terrane magnetic sources. **C:** 3-D gridded
757 block overlaid with interpretations of the rift faults and simplified stratigraphy (interpretations
758 from 2-D seismic line TXZ-16 of Morley et al., 1999 shown in Fig. 2C). Stratigraphic units shown:
759 1 = Precambrian basement), 2 = Permo-Triassic (Karoo Grp.) sequences, 3 = Post-Karoo
760 sequences i.e., Red Bed Grp. and Lake Bed Fm.). **D:** Regional satellite DEM hillshade showing
761 the >600 km extent of the CSZ and its relationships with the Rukwa and Luama segments of the
762 Rukwa Trend. Cross-sections are based on satellite DEM (Luama Rift), and satellite DEM,
763 aeromagnetics, and 2-D seismic data interpretation (Rukwa Rift).

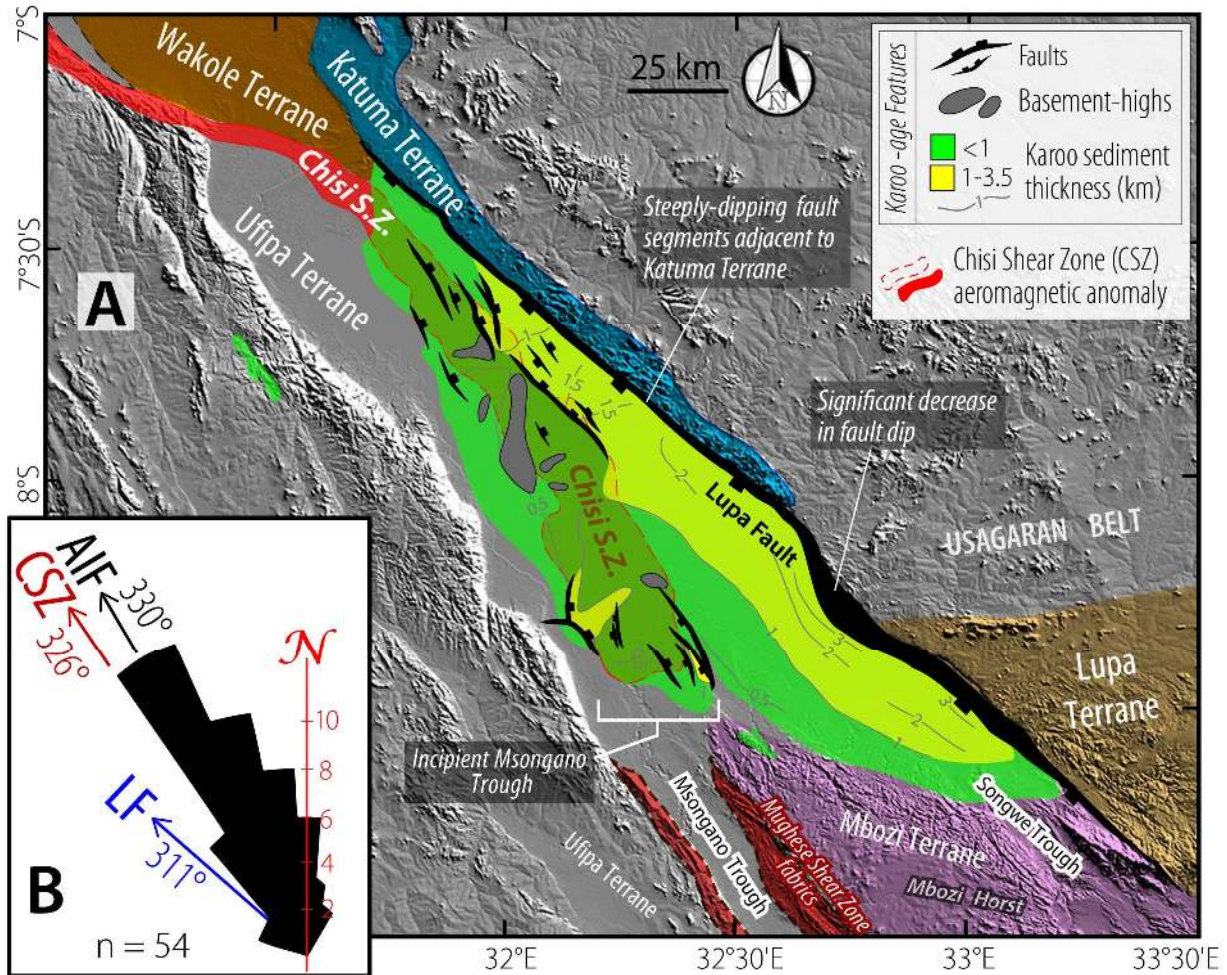
764
765
766
767
768
769
770
771
772
773
774
775
776
777
778
779
780
781
782
783
784
785
786
787
788
789
790
791
792
793
794
795
796

797
 798
 799
 800
 801
 802
 803
 804
 805
 806
 807
 808
 809
 810
 811
 812
 813
 814
 815



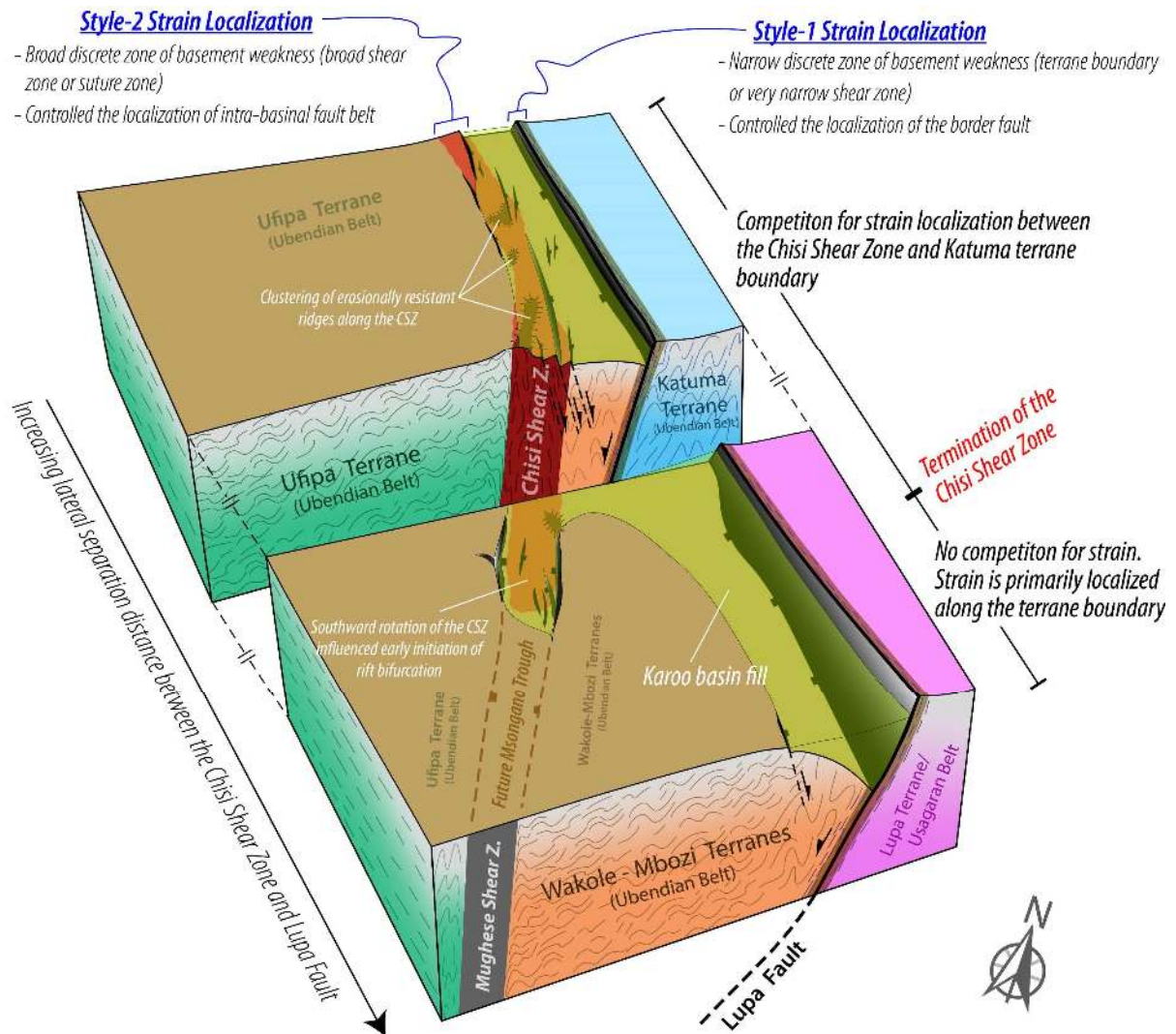
816 **Figure 4. A:** Map of vertical derivative of the aeromagnetic grid overlaid on satellite DEM
 817 hillshade, showing the section of the Rukwa Rift (white dashed lines) along which, the
 818 measurements plotted in Figures 4C-D were taken. **B:** Frequency-azimuth distribution of the
 819 Karoo-age intra-basinal faults (KIF; measured in this study). CSZ = Chisi Shear Zone, LF = Lupa
 820 Fault. Arrows represent the mean trend of the associated structure. **C:** Plot showing along-rift
 821 distribution of (i.) line-length measurement of the Top-Karoo surface as estimates of Karoo-age
 822 tectonic extension (for the Lupa and intra-basinal faults), Lupa Fault dip angle, and Top-Basement
 823 offset along the Lupa Fault, and (ii.) lateral separation distance between the CSZ and the Lupa
 824 Fault. **D:** Plot showing the along-rift variation of % total Karoo-age extension accommodated by

825 the Lupa Fault and the intra-basinal faults up till the CSZ termination (displayed as stacked area
 826 plot in Fig. 4C).
 827
 828
 829
 830



831
 832 **Figure 5. A:** Satellite DEM hillshade of the Rukwa Rift, overlaid with the Karoo structural features
 833 (faults and basement ridges), Karoo isopach map (from Morley et al., 1992, 1999), Chisi Shear
 834 Zone magnetic anomaly, and the relevant surrounding basement terranes. **B:** Frequency-azimuth
 835 distribution of all the faults (Permian-Quaternary) in the Rukwa Rift (digitized from Morley et al.,
 836 1992). ARF = “All Rukwa Rift faults” and black arrow showing their mean trend; LF = “Lupa
 837 Fault” and blue arrow showing its approximate trend; CSZ = “Chisi Shear Zone” and brown arrow
 838 showing its approximate trend within the rift axis.
 839

840
 841



844 **Figure 6.** Cartoon illustrating some of the key observations in this study, showing how the
 845 structure of discrete zones of basement weakness influenced strain localization styles and along-
 846 rift distribution of extension during the early phase of tectonic extension in the Rukwa Rift.