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1 **Spatio-temporal trends in normal-fault segmentation recorded by**
2 **low-temperature thermochronology: Livingstone fault scarp,**
3 **Malawi Rift, East African Rift System.**

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12 **Abstract**

13 The evolution of through-going normal-fault arrays from initial nucleation to
14 growth and subsequent interaction and mechanical linkage is well documented in
15 many extensional provinces. Over time, these processes lead to predictable spatial
16 and temporal variations in the amount and rate of displacement accumulated along
17 strike of individual fault segments, which should be manifested in the patterns of
18 footwall exhumation.

19 Here, we investigate the along-strike and vertical distribution of low-
20 temperature apatite (U-Th)/He (AHe) cooling ages along the bounding fault system,
21 the Livingstone fault, of the Karonga Basin of the northern Malawi Rift. The fault
22 evolution and linkage from rift initiation to the present day has been previously
23 constrained through investigations of the hanging wall basin fill. The new cooling

24 ages from the footwall of the Livingstone fault can be related to the adjacent
25 depocenter evolution and across a relay zone between two palaeo-fault segments.
26 Our data are complimented by published apatite fission-track (AFT) data and reveal
27 significant variation in rock cooling history along-strike: the center of the footwall
28 yields younger cooling ages than the former tips of earlier fault segments that are
29 now linked. This suggests that low-temperature thermochronology can detect fault
30 interactions along strike. That these former segment boundaries are preserved within
31 exhumed footwall rocks is a function of the relatively recent linkage of the system.

32 Our study highlights that changes in AHe (and potentially AFT) ages
33 associated with the along-strike displacement profile can occur over relatively short
34 horizontal distances (of a few kilometers). This is fundamentally important in the
35 assessment of the vertical cooling history of footwalls in extensional systems:
36 temporal differences in the rate of tectonically driven exhumation at a given location
37 along fault strike may be of greater importance in controlling changes in rates of
38 vertical exhumation than commonly invoked climatic fluctuations.

39 *Keywords: Apatite Helium thermochronology; normal-fault evolution; fault linkage;*
40 *East African Rift System*

41

42 **1. Introduction**

43 The displacement across a crustal-scale normal-fault is accommodated by a
44 combination of hanging wall subsidence and, as a consequence of isostatic
45 adjustments, to a lesser extent corresponding footwall uplift (e.g., Jackson and
46 McKenzie, 1983; Walsh and Watterson, 1987; Stein and Barrientos, 1985). This

47 process leads to the vertical exhumation of rock through the footwall over time, and
48 should be a function of the amount and rate of displacement both across and along
49 strike of the fault at a first order, modified by any climatically driven variation in
50 exhumation. The amount and rate of displacement along individual normal-faults
51 within developing fault arrays evolves in a predictable manner (e.g., Walsh and
52 Waterson, 1987, 1991; Gupta et al., 1998; Cowie et al., 2000; Trudgill and
53 Cartwright, 1994). Due to the increase in relief and surface-process gradients this
54 spatial distribution of displacement accumulation along an evolving fault array should
55 be manifested in the patterns of footwall exhumation. While many studies have
56 utilized low-temperature thermochronology to determine changes in vertical rates of
57 exhumation, specifically to constrain the onset of rifting (Fitzgerald, 1992; Bauer et
58 al., 2010; Woodruff et al., 2013; Torres Acosta et al., 2015) or to elucidate changes
59 in climatically driven exhumation (e.g., Ehlers et al., 2006; Spiegel et al., 2007), few
60 studies have utilized the technique to determine along-strike fault displacement
61 variations through time. Armstrong et al. (2004) demonstrated a lack of along-strike
62 variation in apatite (U-Th)/He ages (AHe) for the Wasatch fault, USA, such that
63 mechanical segmentation of the fault is not preserved despite its segmented footwall
64 topography. Conversely, Krugh (2008) demonstrated different cooling ages in relay
65 zones that correspond to different timing of mechanical linkage between fault
66 segments along the Wassuk Range in the Basin and Range province, USA.

67 The lack of thermochronology case studies is surprising as the manner by
68 which extensional fault systems grow is well documented from natural examples and
69 numerical modelling. Normal-faults typically grow through a combination of fault-tip
70 propagation and displacement accumulation, and through fault linkage to produce
71 arrays comprising a series of kinematically linked segments (e.g., Dawers et al.,

72 1993; Gupta et al., 1998; Cowie et al., 2000). Isolated faults propagate in length as
73 stress builds up at the fault tip; when this overcomes the yield strength of the
74 surrounding rock, it ruptures (e.g., Cowie and Scholz, 1992). As isolated faults
75 propagate toward each other their stress fields interact to produce a feedback effect,
76 whereby the displacement on one structure causes slip on another (Cowie, 1998;
77 Gupta and Scholz, 2000). The anticipated maximum displacement on a single fault is
78 scaled to its overall length (Schlische et al., 1996; Dawers and Anders, 1995).
79 Additionally, the spatial distribution of displacement along strike of individual faults
80 occurs in a relatively predictable pattern due to the mechanisms of fault growth and
81 linkage (Figure 1). Fault-displacement profiles, that is the amount of displacement
82 accumulated across the fault versus distance along strike, of isolated faults have a
83 bell-shaped (often flat topped) profile with the greatest amount of displacement
84 occurring toward the center of a fault and displacement minima at the fault tip (Walsh
85 and Waterson., 1991; Dawers et al., 1993; Cartwright et al., 1995). The idealised
86 displacement profile demonstrated for isolated faults is also documented for evolving
87 fault arrays. Interacting faults achieve a combined displacement for the entire length
88 of the linked array, with maximum displacement in the center and minimum at the tip
89 (e.g., Gupta et al., 1998; Cowie et al., 2000; McLeod et al., 2000). Not all faults
90 achieve this displacement profile through a constant interplay of propagating length
91 and then acquiring displacement. Some isolated segments achieve their length early
92 and then accrue displacement. In this case, fault length is often determined by the
93 interaction with other propagating faults, and structures are initially under-displaced
94 until the bell-shaped profile is achieved (Walsh et al., 2002).

95 The ideal model of fault interaction (Figure 1) commences with nucleating
96 isolated normal-faults (Cowie, 1992). As these isolated faults propagate they interact

97 with neighboring structures along strike (Cowie et al., 2000). Their fault tips may
98 propagate past one another, and stress builds up within the region of overlapping
99 fault tips; while they are inhibited in lengthening further as the fault tip propagates
100 into the region of reduced stress on the neighboring fault (Gupta and Scholz, 2000).
101 This leads to a steeper displacement gradient close to the overlapping fault tips, and
102 the displacement profile of the individual fault segments becomes asymmetrically
103 skewed toward one another as they interact (Peacock and Sanderson, 1991; Nicol et
104 al., 1996).

105 Instead of continuing to propagate as an isolated fault, the fault segments
106 become mechanically linked across the region of overlap, or “relay” zone to form a
107 single through-going fault, often abandoning the fault tips as the relay is breached
108 (e.g., Walsh and Watterson, 1991; Peacock and Sanderson, 1991; Trudgill and
109 Cartwright, 1994).

110 During this interaction, therefore, the overall length of the fault becomes the
111 combined length of the overlapping fault segments. Where previously there was
112 minimal displacement at the former fault tips, this region is now the center of the
113 through-going fault after linkage. Thus the displacement amount and rate within the
114 relay zone increases as the fault moves towards a bell-shaped displacement profile,
115 with maximum displacement in the center, and minimum at the tip (Gupta et al.,
116 1998). This process can lead to faults appearing to be “under-displaced” in the
117 region of a former relay zone as the amount of displacement in the center adjusts to
118 the new fault length (Gupta et al., 1998). Not all faults will follow this idealised
119 pattern. In the same manner as some fault segments can propagate their length first
120 and later accrue displacement; fault arrays can rapidly acquire their length and
121 subsequently accrue displacement (Morley, 1999).

122

123 These patterns of fault growth and linkage should be manifested in AHe
124 dating, as the cooling history along fault strike should vary, reflecting the different
125 rates of displacement accumulation on a propagating normal-fault array.

126 Here, we apply apatite (U-Th)/He dating to the segmented border fault system
127 of the Karonga Basin of the Malawi Rift, East African Rift System (EARS; Figure 2).
128 The structural evolution of the Karonga Basin is well constrained from previous
129 studies that utilized seismic reflection data (Mortimer et al., 2007). Based upon the
130 distribution of depocenters, the pattern of border fault evolution through the linkage
131 of fault segments, and the presence of a relay zone has been established. Here, we
132 investigate whether this established evolution of the border-fault array is reflected in
133 the footwall AHe cooling ages. Specifically, we aim to determine whether variations
134 in AHe ages exist at similar elevations along-strike, reflecting fault segmentation. In
135 contrast to other studies that have looked to reveal fault segments through AHe
136 analyses, we know the segmentation history and do not rely upon footwall
137 morphology. Instead we evaluate whether the known variations in the spatio-
138 temporal displacement distribution are recorded in the exhumational cooling of the
139 footwall.

140 **2. Geologic setting**

141 The EARS (Figure 2) comprises two geologically distinct, and strongly
142 contrasting branches; the largely amagmatic western and magmatic eastern
143 branches passing either side of the Tanzania Craton, an area of regional doming
144 (Wichura et al., 2015), and superimposed upon existing Proterozoic mobile belts
145 (McConnell, 1972; Shackleton, 1993). The eastern rift is a narrow zone of

146 extensional basins in northern Tanzania and Kenya with well documented spatio-
147 temporal variations in the onset of rift-related volcanism (George et al., 1998;
148 Ebinger and Sleep, 1998; Ebinger, 1989; Morley et al., 1992; Morley, 1999; Michon,
149 2015) that commenced at ca. 43 Ma in Ethiopia. The western rift comprises a series
150 of deep half-graben basins with footwall escarpments rising 1-2 km (Ebinger, 1984,
151 1989; Rosendahl, 1987). The onset of rifting within the western rift varies with the
152 Rukwa Rift initiated 26-25 Ma (Roberts et al., 2012); and <10 Ma in the Albertine
153 graben (Pickford and Senut, 1994), while it has been shown that extension-related
154 exhumation in the Rwenzori Mountains of Uganda began during the Eocene (Bauer
155 et al., 2013). Rifting within the Malawi Rift has previously been considered to have
156 commenced at the onset of volcanism, ca. 8.6 Ma (Ebinger et al., 1993). However,
157 based on apatite fission-track cooling ages, Cenozoic cooling within the Malawi Rift
158 commenced after 40 Ma, with most rapid cooling occurring in the past 20 Ma (van
159 der Beek et al., 1998).

160 The Malawi Rift is in the southernmost rift of the western branch of the EARS
161 and the Karonga Basin refers to the northern lake-filled basin within the rift (Figure
162 2). It is bounded to the east by a large (>90 km long) crustal-scale normal-fault, the
163 Livingstone fault, with >2000 m of footwall relief (relative to lake level); the fault
164 accommodates >4 km of sediments in its hanging wall beneath the deep (up to 600
165 m) Lake Nyasa (Figure 2). The basin fill and border-fault architecture has been well
166 documented from seismic reflection data (Rosendahl, 1987; Ebinger et al., 1993,
167 1987; Scholz, 1989; Mortimer et al., 2007). The sedimentary fill of the hanging wall
168 comprises three depositional sequences (Scholz, 1989; Ebinger et al., 1993;
169 Mortimer et al., 2007): Sequence 1 >8.6 Ma to 2.3 Ma, Sequence 2 from 2.3 Ma to
170 1.6 Ma, and Sequence 3 from 1.6 Ma to present (Ebinger et al., 1993).

171 The border fault consists of three segments: the northern, central and
172 southern segments (Figure 2). The tips of the central and southern segments overlap
173 where there is a notable step in the shoreline, corresponding to a relay structure,
174 close to the village of Lupingu (red star on Figure 2b). This relay is adjacent to the
175 deepest portion of the modern-day Lake Nyasa. The northern and central segments
176 linked to form a continuous structure early in the basin history, and the
177 corresponding segment boundary is marked by a small step in the lake shoreline
178 (Figure 2; Mortimer et al., 2007). At the top of the Livingstone escarpment is a
179 broad, high-elevation (>2000 m) plateau region (Figure 2).

180 In addition to the existing seismic studies on the basin, we utilize a
181 reprocessed dataset of the PROBE (Scholz, 1989) survey to better constrain the
182 location of the offshore fault tip of the southern fault segment. A monocline located
183 along strike of the southern segment, with growth strata adjacent to it, pinpoints the
184 location of the fault tip (Figure 2) and defines the 6 km wide relay zone between the
185 two fault segments. This monocline developed late during the deposition of
186 Sequence 2 (post 2.3 Ma), recently in the border-fault evolution. This implies that
187 mechanical linkage occurred relatively recently. Determining the location of the fault
188 tip for the central segment within this relay zone relies upon footwall relief from the
189 SRTM data.

190 **2.1 Evolution of the Livingstone fault**

191 The evolution of the border fault has previously been established (Mortimer et
192 al., 2007; Figure 3). Importantly, at each stage or Sequence of strata in the hanging
193 wall units, the most rapid displacement accumulation is likely to have been located in
194 regions of greatest displacement, identified by regions of greatest sedimentary

195 thickening (Figure 3b i-iii). Initially, the north and central segments were associated
196 with significant depocenters from Sequence 1 (Figure 3i), and most of the
197 displacement occurred in these regions (Figure 3b i). The central and southern
198 segments were isolated (scenario A in Figure 1), consistent with the onset of rifting
199 occurring earlier in the north than south of the basin (Ebinger et al., 1993; Mortimer
200 et al., 2007). During deposition of Sequence 2 (Figure 3ii) there was a shift in
201 deposition toward the center and south of the basin as these two segments
202 overlapped and the relay zone developed between the central and southern
203 segments. The depocenters associated with the central segment moved toward this
204 relay zone, although the relay was clearly a ramp between the two faults (scenario B
205 in Figure 1). At this time, footwall uplift would have migrated toward the relay zone as
206 displacement skewed (Figure 3ii). The northern segment continued to accrue
207 displacement. During Sequence 3 (Figure 3iii), the relay zone and southern segment
208 are important depocenters, and are regions of highest displacement. The relay zone
209 was breached during the latest stages of Sequence 3 and sediment was deposited
210 into the hanging wall of this breaching fault as the depocenters migrated towards the
211 relay zone (Mortimer et al., 2007). At this time, the fault tip of the central segment
212 was captured into the hanging wall of the through-going fault (scenario C Figure 1).
213 The cumulative displacement along the border fault (Figure 3iv) shows time to
214 basement ranges from 2600 to 4000 ms two-way travel time (twt). Evident from this
215 is the segmentation along the fault that existed during the deposition of Sequence 1.
216 This sequence accrued significant displacement, and combining the total
217 displacement through each stage is still reflected in the cumulative throw today
218 (Figure 3i-iii). The greatest amount of offset of the basement is adjacent to the
219 central segment. The total displacement adjacent to our samples in the northern and

220 central segments is similar overall. What this cumulative throw does not highlight is
221 that the greatest, and probably most rapid, displacement occurring in the most recent
222 history to the present-day, corresponds to where the lake is deepest (the deepest
223 depocenters being created in the final stages). This is located adjacent to the relay
224 zone and toward the southern segment (Figure 2b). These patterns of fault evolution
225 and hanging wall subsidence can be considered to reflect where the greatest amount
226 and rate of associated footwall uplift and exhumation were likely to have been
227 occurring through time; the depocenter distribution thus can be utilized as a proxy for
228 fault controlled footwall exhumation patterns in the absence of footwall markers for
229 absolute displacement (Figure 3i-iv).

230 **2.2 Existing Low-Temperature Thermochronology**

231 Van der Beek et al. (1998) used apatite fission track (AFT) analyses to
232 investigate the denudational cooling history of the Livingstone escarpment and
233 plateau. The data reveal at least three episodes of cooling and denudation related to
234 regional tectonic events, the most recent in the Cenozoic associated with the present
235 day EARS. AFT ages from the footwall scarp on the central fault segment (the
236 location of the samples of van der Beek et al. (1998) are indicated on Figure 2c)
237 range between 178 and 50 Ma and exhibit a positive age-elevation profile. A single
238 AFT age close to the fault tip and at lake level (460 m; sample DD485a; Figure 1) is
239 128 Ma; this is anomalously old compared to a sample from the base of the scarp
240 (675 m elevation), which yielded an AFT age of 50 Ma. The data suggest that the
241 center of the fault segment underwent 2.2 ± 0.4 km of exhumation in the Cenozoic,
242 assuming a geothermal gradient of 25-30°C/km. In this study, we aim to determine
243 whether apatite He cooling ages better constrain the evolution of Cenozoic rifting
244 within this region of the Malawi Rift.

245

246 **3. Apatite He dating Methods**

247 The AHe dating technique relies on the production of alpha particles (^4He) as a
248 result of radioactive decay of U, Th and Sm isotopes (Farley et al., 1996). The rate at
249 which He diffuses through a crystal depends on the grain size, time, radiation
250 damage and temperature. Helium starts to be retained within apatite crystals at less
251 than 80°C , with retention increasing dramatically from $\sim 40^\circ\text{C}$; between ~ 80 and 40°C
252 is the partial retention zone (PRZ). The AHe ages therefore record the time since
253 these samples were open for He diffusion at temperatures in excess of 40°C . The
254 technique is, therefore, particularly sensitive to processes active in the uppermost
255 part of the crust. We analysed apatites from 10 samples from the region surrounding
256 the relay zone, including two from the summit plateau (TAN 10 and 14), one near the
257 top of the escarpment (TAN 15), four (TAN 16, 17, 18, 20) at, or close to, lake level
258 on the central fault segment, and three (TAN 3, 7, 9) from the northern segment
259 (Figure 2). Apatites were separated using standard heavy-mineral separation
260 techniques. The number of analyses was limited by the quality of the apatite (no
261 inclusions, good crystal morphology) in the samples. Between 1 and 4 aliquots of 1
262 to 3 apatite grains were hand-picked for each sample at 218x magnification using a
263 stereographic binocular microscope. To minimize grain-size variation effects, crystals
264 of similar radius were selected for each aliquot. He, U and Th analyses were
265 conducted following procedures outlined in Foeken et al. (2006). Correction for He
266 recoil loss was made using standard procedures (Farley and Stockli, 2002). The total
267 analytical uncertainty of He ages of each aliquot is approximately 8%, governed by
268 uncertainty in blank corrections and U and Th spike concentrations. Aliquots that
269 yielded analytical uncertainties greater than 10% ($n = 5$), and that are older than AFT

270 ages ($n = 5$) are not reported. He, U and Th concentrations, grain dimensions,
271 uncorrected ages and corrected ages of our samples are reported in Table 1. Age
272 reproducibility was variable (Table 1), as a result weighted mean ages with
273 appropriate error propagation which takes into account repeat grain-age variance are
274 reported (Table 2) and discussed in the text. The cause of the variability is not clear.
275 Individual samples showed some variation in U and Th content e.g. Tan 14 U: 10-62
276 ppm; Th: 45-116, whilst others e.g. Tan 16 U: 31-37 ppm; Th: 6.6-7.6 ppm; showed
277 little. As a result effective uranium (eU) ($[U] + (0.235*[Th])$ which is a proxy for alpha
278 productivity) (Table 1) varies within and between samples, however, there is no
279 systematic correlation between aliquot age and eU content (see Appendix A).

280 AHe grains were modelled using the HeFTy (v1.8.2) computer program
281 (Ketcham, 2005) using measured U, Th, grain size and uncorrected AHe ages. The
282 time-temperature histories use an inverse modelling approach, for each thermal
283 history the model was constrained by a surface temperature of 20°C and a fission-
284 track age of 50 Ma (DD490; van der Beek et al., 1998); 120 Ma if located in the relay
285 zone or 220 Ma if located on the plateau (DD478; van der Beek et al., 1998). The
286 alpha stopping distance corrections of Ketcham et al. (2011) were used. The
287 calibrations of both Farley (2000) and the radiation damage and annealing model
288 (RDAAM) of Flowers (2009) was implemented, the latter specifically for the samples
289 from the top of the Livingstone plateau, which potentially experienced slow to
290 moderate cooling (1-0.1°C/km). Individual aliquot data were modelled for each
291 sample with the final thermal history profile that is used in the discussion produced to
292 represent the variability of the best fit solutions within the sample set (Figure 4).
293 Overall within sample trends are similar suggesting that despite the age variability,
294 the grains have experienced similar cooling histories.

295 **4. RESULTS: Apatite U/Th-He age distribution.**

296 The lake-level samples between the central and southern segments span 10 km
297 along fault-strike, and there is more than 30 km between these and samples from the
298 northern segment (Figure 2 for location). Samples TAN 17 and TAN 18 are located
299 close to the base of the vertical profile of van der Beek et al. (1998), while the
300 location of sample TAN 16 is is virtually identical to their sample DD485a (AFT age =
301 128 Ma at 460 m elevation).

302 The weighted mean AHe ages (Table 2) range from 2.1 ± 1.3 Ma to 197.4 ± 2.7
303 Ma with the age distribution consistent with the distribution of sampling both along
304 fault strike and from a near-vertical profile from the top of the plateau to the base of
305 the escarpment (Figures 3 and 4). Cenozoic ages occur closest to lake level while
306 the oldest ages (e.g., TAN 10: 197.4 ± 2.7 Ma) were determined for samples from the
307 plateau, and at an elevation greater than 1500 m (TAN 14). To the south, the
308 youngest ages are from samples located toward the center of the central fault
309 segment (TAN 17 = 12.5 ± 7.5 Ma and TAN 18 = 7.1 ± 3.2 Ma). TAN 16 (29.7 ± 1.2
310 Ma), the oldest lake-level sample, is located close to the fault tip. TAN 20 (21.6 ± 9.2
311 Ma), located within the relay zone and at 673 m elevation, yields a similar age to
312 TAN15 (22.5 ± 3.4 Ma) from the southern segment at 1270 m elevation. The
313 youngest age, TAN 7 (2.1 ± 1.3 Ma), is reported from the northern segment, and is
314 considerably younger than the other adjacent Oligo-Miocene ages reported. TAN 3
315 (14.2 ± 1.1 Ma) is within reported error of TAN 9 (12.1 ± 3.5) close to the center of
316 the northern segment at lake level (Figure 4).

317 AHe ages not only vary along-strike but also vertically, as shown by the age-
318 elevation relationship (AER; Figure 5). These oldest AHe samples are from the

319 summit and plateau of the scarp; closer to lake level (460 m) is a spread of younger
320 (Oligo-Miocene) AHe ages (Figure 5). AERs are frequently used to constrain the
321 timing of onset of rapid exhumation or, in this case, the onset of extensional faulting
322 and rift initiation. Given the scatter of Cenozoic ages, care must be taken when
323 considering the AER for the Livingstone escarpment. Samples used for the AER are
324 TAN 14 and TAN 15 that are vertically directly above one another and within the
325 same fault segment, and TAN 20, the closest sample to that profile. There is a
326 distinct break in slope below 1500 m (between TAN 14 and TAN 15) with the AER
327 recording at least one order of magnitude increase in the rate of exhumation. This
328 dramatic change takes place before the late Oligocene/early Miocene (23 ± 3 Ma).
329 This is likely the latest time of onset of Cenozoic exhumation in this part of the
330 Malawi Rift. It is in agreement with the AER from apatite fission-track data that
331 indicated most cooling has occurred in the last 20 million years (van der Beek et al.,
332 1998), and is contemporaneous with the dated onset of Cenozoic rifting in the
333 Rukwa Rift (Roberts et al., 2012) immediately to the north (Figure 2a). This is
334 significantly earlier for the Malawi Rift than has been previously postulated.

335 The thermal history modelling for all aliquots measured (Figure 4) shows that the
336 samples from the plateau and the top of the footwall escarpment (TAN 10 and TAN
337 14) experienced slow cooling through the PRZ from the Jurassic. In contrast,
338 samples from the footwall escarpment have all cooled to the surface during the
339 Cenozoic. These samples exhibit somewhat different cooling paths depending upon
340 their position, both vertically and along strike. Samples TAN 15 (1289 m), TAN 16
341 (560 m, at the fault tip) and TAN 20 (~700 m, southern segment) have similar
342 modelled cooling paths, starting relatively flatter and then steepening slightly as they

343 entered the PRZ between ca.35 and 20 Ma, from which time they cooled relatively
344 monotonically.

345 Samples TAN17 and 18 were exhumed through the PRZ more recently (since
346 c.15 and 9 Ma respectively; Figure 4; Supplementary figure) and more rapidly than
347 other parts of the border fault. This would be anticipated given their position at the
348 center of the fault segment (e.g. Gupta et al., 1998) (Figure 3i-iii). The fact that they
349 do not record their exhumation onset as early as the vertical profile might suggest
350 (i.e., late Oligocene-early Miocene) is potentially due to the greater amount of
351 material that would be exhumed through the central portion of the fault or temporally
352 variable fault-segment activity. Samples TAN 17 and 18 (Figure 4c) record more
353 rapid, tectonically driven exhumation in the past 10 Ma at the center of the structure,
354 as discussed below.

355 From the northern fault segment (Figure 4b), samples TAN 3 and TAN 9 exhibit
356 similar cooling paths; TAN 3 commenced cooling slightly earlier (since c.20 Ma) and
357 more slowly than TAN 9 (since c.15 Ma). These samples are from close to the center
358 of the fault segment, have similar (although later) cooling histories, and are located
359 in a similar position to TAN 18 and TAN 17 in the central fault segment. TAN 7 is
360 exceptionally young (2.1 Ma; Table 2) and may have been reset by hydrothermal
361 fluid flow. Fluid flow was advocated by van der Beek et al. (1998) elsewhere in the
362 rift to explain young AFT ages and this sample is located along a cross-cutting fault
363 (Mortimer et al., 2007) that might explain the fluid pathway. No thermal history
364 models are therefore presented for this sample.

365

366 **5. Discussion**

367 The new low-temperature cooling ages clearly demonstrate that the fault tip and
368 relay zone (TAN 16, TAN 20) and the northern segment (TAN 3, TAN 9) commenced
369 exhumation in the early Miocene while the center of the southern segment (Tan 17,
370 Tan 18) commenced exhumation more recently. This agrees with the inferred
371 southward propagation rifting within the Malawi Rift (Ebinger et al., 1993). This is
372 consistent with the thicker sediments of the Sequence 1 depocenter adjacent to the
373 northern segment (Figure 3; Mortimer et al., 2007). It is unlikely that ages that record
374 the onset of rifting will be preserved close to lake level as the rapid exhumation
375 associated with fault linkage and changes in displacement rate are probably of
376 greater magnitude than earlier regional uplift associated with Cenozoic rifting. The
377 individual cooling paths are, therefore, more likely to illustrate local changes in
378 displacement rate rather than recording the regional exhumation. The AER shows a
379 break in slope before the Early Miocene (Figure 5) that coincides with the onset of
380 Cenozoic rifting in the Rukwa Rift (Roberts et al., 2012). While this link should be
381 treated with caution, it should also be noted that the cooling ages at the fault tips
382 (which are more likely to preserve regional onset as displacement rates here were
383 lower) are similar, supporting the contention that it does record the timing of onset of
384 *regional* Cenozoic rifting effects in the Malawi Rift.

385 We consider the variation in AHe ages and cooling paths along the fault
386 segments of the Malawi Rift, in particular the central segment, in the context of the
387 evolution of the border fault system and find their distribution along the fault
388 compelling despite the limited number of data. Rocks closer to the fault tips have
389 experienced a more protracted cooling history than those closer to the segment
390 centers in both the northern and central-southern segments. Additionally,
391 segmentation appears to be preserved along the fault: TAN 16 at the fault tip records

392 older, more slowly exhumed rocks; despite the present-day scenario of a fully linked,
393 through-going normal-fault bordering an under-filled basin with the maximum
394 displacement at its center (Figure 3; and lake bathymetry, Figure 1).

395 Within this context, we combine our AHe ages from the Malawi Rift, with the
396 established normal-fault evolution (Mortimer et al., 2007; Figure 3) and predicted
397 models of normal-fault evolution (e.g., Gupta et al., 1998) and envisage the cooling
398 path of rocks at different locations along strike as they are vertically exhumed in an
399 evolving, interacting and linking normal-fault system. This allows us to present a
400 model (Figure 5), focusing upon the relationship between cooling ages along the
401 central and southern segment, but relevant for the northern segment, which not only
402 accounts for the observed AHe age distribution in the Malawi Rift, but also considers
403 the particular scenarios that have led to segmentation being preserved in the cooling
404 paths here.

405 In a predicted fault profile of displacement along fault strike (*sensu* Gupta et al.,
406 1998), the center of an isolated fault will experience more rapid footwall exhumation
407 than the tip of a fault, as this is where displacement is greatest. Therefore, rocks in
408 the center of the fault segment will begin vertical exhumation earlier and more rapidly
409 than those at the fault tip (Figure 6 a and b; stages 1 and 2).

410 Faults rarely grow in isolation, but interact along strike leading to a skew in the
411 profile in such a way that the displacement (and exhumation) rate increases toward
412 the overlapping fault and relay zone as the fault segments become linked and
413 effectively become an integral part of the full length of the through-going structure.
414 The central segment is today, mechanically linked to the southern segment across
415 the relay zone. These two segments have interacted and experienced a skew in their

416 displacement during Sequence 2 and Sequence 3 when depocenters adjacent to the
417 central and southern fault segments moved toward one another and the relay
418 breached toward the end of the time of deposition of Sequence 3 (Mortimer et al.,
419 2007; Figure 3). Rocks being exhumed close to the former fault tips would
420 experience a more rapid cooling later in their history as the new through-going
421 mechanically linked fault develops that is under-displaced in its center (Figure 6 c to
422 d, stages 3 to 4). The skew in displacement profile can also lead to a steepened
423 displacement gradient toward the fault tip (e.g., Nicol et al., 1996). This might explain
424 the different age and cooling paths of TAN 17 and TAN 18 (with TAN 18 located
425 closer to the fault tip accelerating later) and why the fault tip (TAN 16) does not
426 record any acceleration. This suggests that the fault was “under-displaced” (Figure 6
427 c and d) *sensu* Cartwright et al. (1995). These data are more convincing when
428 considered alongside the existing AFT data (for specific locations see Figure 2),
429 where an anomalously old age for elevation (compared to their vertical profile) of 128
430 Ma (sample DD485a) is recorded at the fault tip of the central segment. AFT ages
431 from the central fault segment at similar elevations such as DD484 and DD480
432 exhibit much younger AFT ages (66 and 50 Ma, respectively). This pattern mirrors
433 that of the AHe ages presented here, further supporting the hypothesis that the fault
434 tip (and the relay region) of the central fault segment is preserved in the cooling
435 ages.

436 The northern and central fault segments are also linked although we do not have
437 the AHe data across this region for comparison. TAN 3 is located closer to the center
438 of the fault segment than TAN 9. In this segment, TAN 9 cooled later and faster than
439 TAN 3, suggesting there was interaction between the northern and central fault
440 segments. The difference in the gradient of the cooling path between TAN 9 and 3

441 (12 km apart) 15 km from the fault tip, compared to TAN 18 and 17 (5 km apart)
442 within 5 km of the fault tip, is possibly related to proximity to the fault tip, as
443 displacement rates increase most rapidly closest to the fault tip during linkage (e.g.,
444 Gupta et al., 1998; Figure 6c).

445 This pattern of increased displacement in the center of the through-going fault
446 has continued along the Malawi Rift into Sequence 3 (Figure 3) where the current
447 subsidence and exhumation are greatest. This region linked during the latest stages
448 of basin evolution, revealed only in the final packages of deposition of Sequence 3,
449 and likely within the past 1 Ma (Mortimer et al., 2007). The relay region remains
450 'under-displaced' and rapidly accrues displacement, leading to a marked increase in
451 exhumation of the footwall as the displacement profile adjusts to the new fault length
452 (Figure 6 e and f; stages 5 and 6).

453 The along-strike age distribution of rocks that have been exhumed to lake level
454 does not reflect the present-day configuration but records earlier fault segmentation.
455 This fault segmentation is preserved in the cumulative throw (time to basement;
456 Figure 2 iv), but is no longer preserved in the footwall profile, or present-day lake
457 bathymetry (Figure 2b). All of these are at their maximum toward the center of the
458 through-going fault adjacent to the relay.

459 Whether or not fault linkage and/or segmentation are likely to be recorded within
460 the distribution of AHe ages along strike is most likely to be related to the timing of
461 mechanical linkage (e.g., Krugh, 2008), which in the Malawi Rift happened ca. 2 Ma
462 (Sequence 3) as demonstrated by the seismic data (Mortimer et al., 2007; Figure 3).
463 Not only is the timing of linkage a factor in recording fault segmentation, but also
464 whether there has been sufficient footwall exhumation to the surface (Figure 6 d-f;

465 Stages 4-6). Of greatest importance is the appreciation of the lag time between the
466 development of the fault-displacement profile and associated footwall topography
467 and the exhumation of rocks to the surface that record the period of rapid cooling
468 through the PRZ associated with this increased displacement rate.

469 Our data in the Malawi Rift, preserve a snapshot of tectonically driven
470 exhumation in which the segmentation is preserved. Beneath the lake surface is an
471 inaccessible 600 m fault scarp. Somewhere along this structure the rocks that record
472 accelerated cooling associated with linkage at ~1.6 Ma have yet to be exhumed to
473 lake level. Van der Beek et al. (1998) utilized a geothermal gradient of 25-30°C/km
474 based on estimates of heat flow in a regional study by Nyblade et al. (1990). Given
475 this geothermal gradient, any samples experiencing a more rapid exhumation since
476 ~ 1.6 Ma would still be ~1 km below the surface; or, with a slightly greater gradient,
477 at lake bed, but still >500m below lake level. Therefore, samples at or above lake-
478 level today should reflect the fault configuration from Sequence 1 and Sequence 2,
479 as rocks cooled through the PRZ, from the later stages of Sequence 2 and
480 Sequence 3 have not yet been exhumed to the surface (Figure 6e; stage 5). Thus,
481 our ages should reflect fault interaction but not the present-day, more rapid
482 displacement accumulation adjacent to the relay, as is the case. AHe ages lower
483 within the footwall would reflect the most recent cooling history and eventually ages
484 along-strike would no longer record the fault segmentation but represent a single
485 through-going structure (Figure 6f). This is perhaps the end-member scenario
486 represented by the history of the Wasatch fault in Utah (Armstrong et al., 2004),
487 where there is no record of separate segments preserved within AHe ages. As
488 suggested by Krugh (2008), different cooling ages in relays along a fault array are
489 determined by when mechanical linkage occurs. The exhumation or preservation of

490 fault segmentation within the footwall rocks is controlled by the timing of mechanical
491 linkage, the geothermal gradient, and rates of displacement across the fault. In the
492 Malawi Rift, we are fortunate that the interplay of these parameters has led to the
493 preservation of the record of segmentation.

494 To thoroughly reveal the fault-segment history would require a rigorous series of
495 horizontal and vertical transects across the footwall that mimic the type of
496 investigation provided by stratigraphic interpretations of a hanging wall. Nonetheless,
497 changes in the rate of vertical exhumation due to the pattern of fault growth and
498 linkage should be thoroughly evaluated if a single vertical profile is being used to
499 determine variations in external driving forces such as climate or the onset of rifting.

500

501 **6. Conclusions**

502 The age-elevation relationship of our data from the Livingstone fault, Malawi,
503 shows that important, regional-scale cooling associated with Cenozoic rifting
504 commenced at ~23 Ma, slightly later than the Rukwa Rift to the north. This is
505 significantly earlier than the onset of volcanics (Ebinger et al., 1993) and previously
506 proposed rift onset; but is in agreement with proposed rapid Cenozoic exhumation
507 since ca. 20 Ma based upon existing AFT cooling ages (van der Beek et al., 1998).

508 Our data show that low-temperature (AHe) thermochronology does record
509 segmentation of the Livingstone border fault, Malawi. This fault segmentation is
510 recorded by along-strike variations in AHe ages that show protracted cooling at
511 palaeo-fault tips, and more rapid cooling toward the center of active fault segments.

512 The AHe age distribution does not reflect the present-day fault configuration of
513 the Livingstone fault, which experiences the maximum displacement in and close to
514 the relay zone, but instead records the fault segmentation from earlier in the basin
515 history.

516 There is a significant lag between fault interaction, linkage, rapid uplift at any
517 given location, and the vertical exhumation of rocks from the PRZ to lake-level that
518 reflect that interaction. The relatively recent linkage (~1.6 Ma) of the central and
519 southern segments of the Livingstone fault emphasizes that older fault segmentation
520 is more likely to be preserved than in older linked systems.

521

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531

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662

663 **Figure Captions**

664 **Figure 1:** Growth and linkage of normal-faults and the predicted corresponding along
665 strike displacement accumulation. The displacement profile is the amount of
666 displacement, D , measured along fault strike, X . The idealised displacement profile
667 for a normal-fault is a bell shaped curve with maximum displacement in the center
668 and zero at the fault tip, such as in A. As two faults propagate toward each other,
669 their tips can overlap (overlapping faults, B), forming a relay ramp. Their stress fields
670 interact and displacement on each fault segment is skewed toward the center of the
671 overlap. Finally, the faults become linked as the relay ramp is breached (C) and the
672 fault is initially under-displaced in the center (compared to an idealised profile). Post
673 linkage displacement is, therefore, greatest in the center of the linked fault, where
674 previously the tips overlapped (B and C are modified from Trudgill and Cartwright,
675 1994).

676 **Figure 2:** (a) Location of the North Basin, Malawi Rift (study area in red box) as the
677 southernmost rift basin of the western branch of the EARS. The northern two thirds
678 of the Malawi Rift are filled by Lake Nyasa, which reaches up to 800 m depth at its
679 deepest portion. We investigate the northernmost basin, the Karonga Basin, of the
680 Malawi Rift. (b) AHe samples (yellow circles) are from the northern segment (TAN03,
681 07 and 09) and from central and southern segment relay zone (enlarged in d) by the
682 village of Lupingu (red star). The present day bathymetry (cool colours deep and
683 warm colours shallow) is deepest adjacent to the relay zone and the southern
684 segment. (c) Enlargement of the relay zone showing the location of AFT samples of
685 van der Beek et al., 1995 (blue circles), and their spatial relationship to our samples.
686 Those labelled are referred to in the text. d.) The Livingstone Escarpment looking

687 from the north of the lake along the northern segment of the border fault system.
688 Samples TAN03, 09, 07 are located along this segment.

689 **Figure 3:** Known evolution of the border fault system (modified after Mortimer et al.,
690 2007). The locations of our samples (yellow circles), and the village of Lupingu (red
691 star) within the relay zone are indicated. a. (i-iii) Isopach (thickness in ms two-way-
692 time) maps for sedimentary sequences and (iv) depth to basement, adjacent to the
693 border fault. b. The evolution of the segmented border fault system with regions of
694 greatest displacement rate, and therefore most likely to experience rapid exhumation
695 indicated (yellow arrows with size reflecting envisaged difference in rates - large fast,
696 small slower) along the segments. These patterns of exhumation and fault
697 segmentation should be reflected in the thermal evolution of the footwall.

698

699 (i) Sequence 1: the northern segment and northern portion of the central segment
700 experienced the most displacement, in particular adjacent to TAN03, 07 and 09;
701 while to the south along the central and southern segments there was significantly
702 less displacement (TAN17, 18 and 20). The south segment fault tip had not
703 propagated into the relay zone at this time.

704 (ii) Sequence 2: the southern segment and central segment are more active,
705 displacement increased adjacent to TAN17 and 18, as the depocenter moved toward
706 the south and the fault tips had propagated past one another.

707 (iii) Sequence 3: the most recent, is a thin succession with a delta entering the
708 under-filled lake from the north, with much sedimentation focussed adjacent to the
709 relay zone. TAN16 and 20 are within the region of overlap between these two fault

710 segments. As the relay structure was breached by a fault (final stages of Sequence
711 3; Mortimer et al., 2007) sediments accumulate in the hanging wall. TAN16 and 20
712 are captured into the footwall of this breached relay as the fault tip of the central
713 segment is abandoned, while TAN17 and 18 remain along the central segment
714 footwall.

715 (iv) two-way-time to basement: is the cumulative effect that encompasses all of the
716 fault displacement that has occurred between rift onset and the present day. The
717 cumulative throw is similar in distribution to Sequence 1 and preserves the fault
718 segmentation. This shows that the greatest cumulative displacement is adjacent to
719 the central fault segment. However, this does not reveal where displacement rates
720 are greatest today - adjacent to the relay and southern segments, as shown by the
721 bathymetry of the lake bed (see Figure 2).

722 **Figure 4:** Results of the modelled cooling path of each sample using the HeFTy
723 computer program (Ketcham, 2005). Samples were modelled with each grain
724 independently, and the cooling paths for individual grains are shown for each sample
725 (solid black lines). Each different portion of the fault array investigated is represented
726 separately to relate the cooling paths to the position of the sample both vertically and
727 along fault strike.

728 The location of samples are shown with (a.) the plateau region (purple); (b.) the
729 northern segment of the Livingstone fault (green) and (c.) the central-south
730 segments including the relay zone in (red for at or close to lake level; orange for
731 escarpment samples). The distribution of AHe ages for each sample is shown in bold
732 (2 sigma errors in brackets) adjacent to the sample location on the maps.

733 **Figure 5:** Age-Elevation relationship (AER) of samples (weighted mean age) from
734 the Livingstone escarpment (see Figure 1 for location). Samples may be considered
735 relating to their position along strike and vertically within the fault array by the
736 following: Livingstone plateau and summit (diamond); northern segment (squares);
737 southern and central segments and the relay zone (triangles). Vertical AER (grey line
738 on graph) and located on the inset (yellow line) through samples close to the fault tip
739 (TAN20), the escarpment (TAN15) and plateau (TAN14). Summit sample TAN10 is
740 considerably further along strike on the plateau (Figure 1). The wide range of ages at
741 or close to lake level is likely to be associated with differing displacement rates along
742 fault strike, see text for discussion.

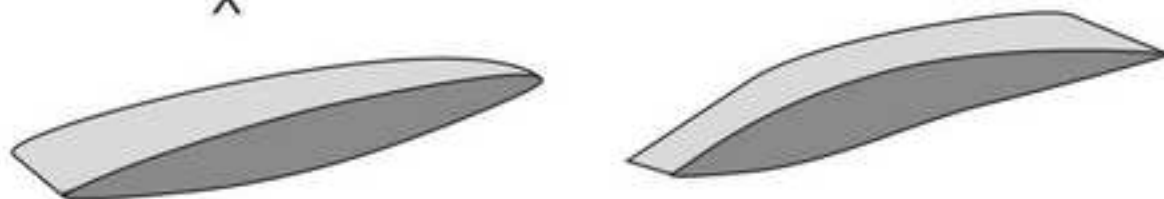
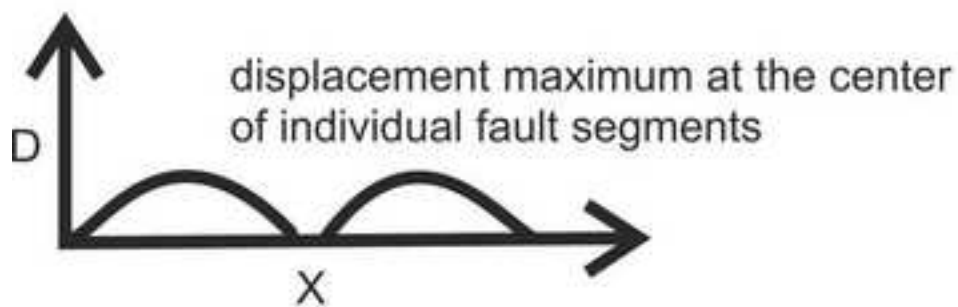
743 **Figure 6:** Envisaged tectonically driven vertical cooling paths of rocks through the
744 Partial Retention Zone (PRZ) resulting from footwall uplift and exhumation (grey
745 shading) associated with normal-fault displacement (D). Patterns of footwall
746 exhumation change as two fault segment link to become a single through-going fault.
747 Rocks that enter the PRZ at the same time are represented by dots of the same
748 colour (t=0 to t=6; stages 1-6). Spatio-temporal variations in tectonically driven
749 exhumation lead to rocks of the same cooling age reaching the surface at different
750 times. Each figure shows the cooling path of rock through the PRZ corresponding to
751 the evolution of the displacement profile along the fault.

752 The along-strike lake-level age distribution (coloured dots along lake-level;
753 stages 4-6) will at times reflect earlier fault segmentation with older ages in the
754 center of the linked array (stage 4 and 5), despite the footwall topography
755 corresponding to a single through-going fault.

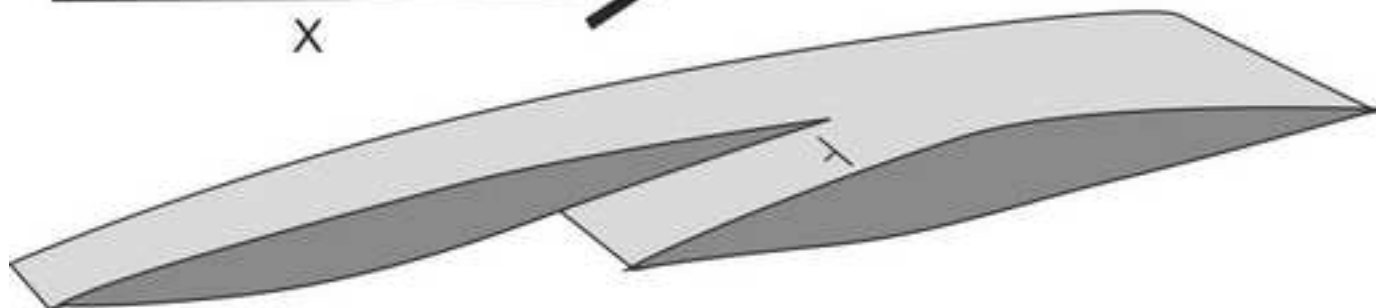
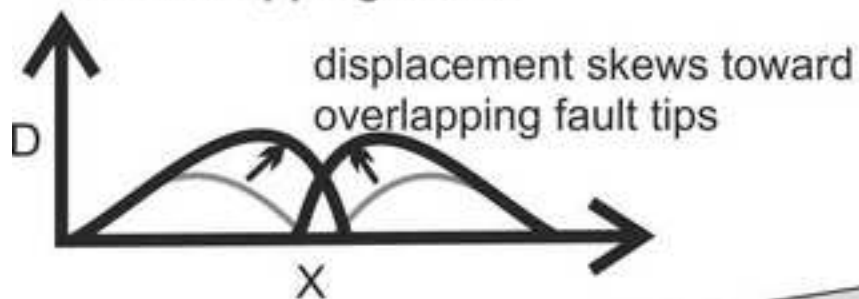
756 Eventually, sufficient exhumation occurs and segmentation is no longer
757 recorded at lake-level, and rapid exhumation in the center corresponds to the
758 youngest ages exhumed. We envisage a Stage 5 scenario for the Malawi Rift, where
759 linkage occurred too recently (~2 Ma) for samples whose cooling path records the
760 present day displacement to have been exhumed to lake-level.

Figure 1 low res
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A. Isolated faults



B. Overlapping faults



C. Postlinkage

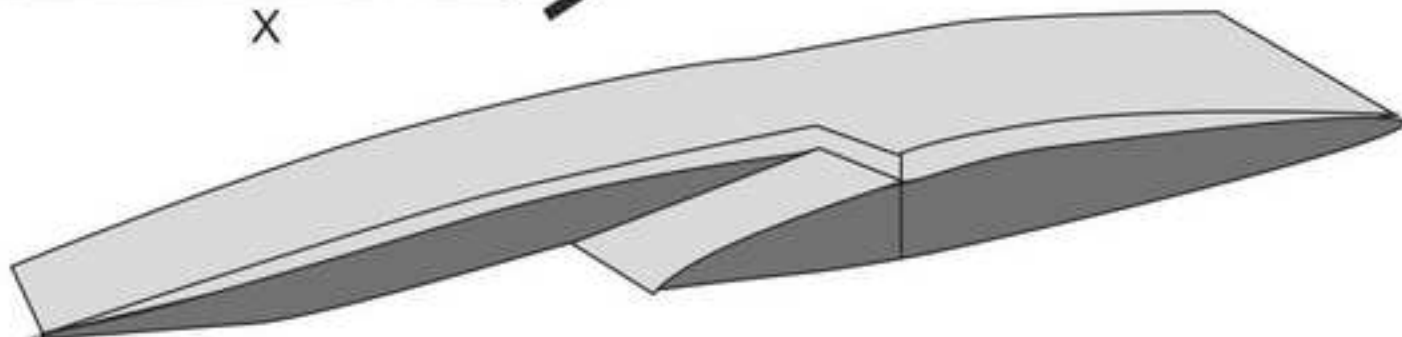
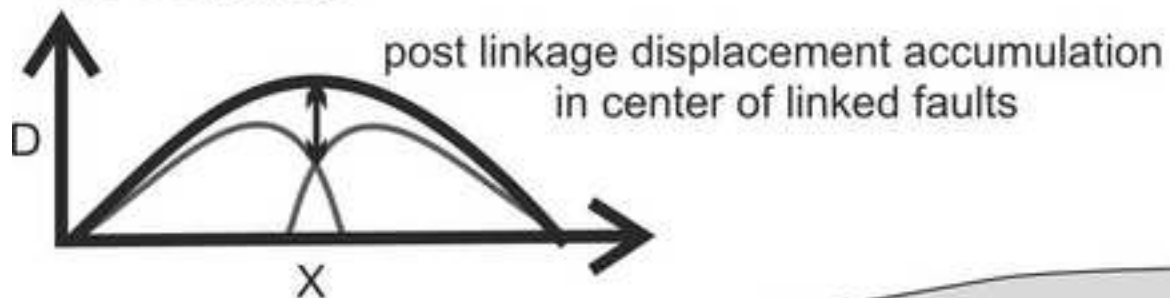


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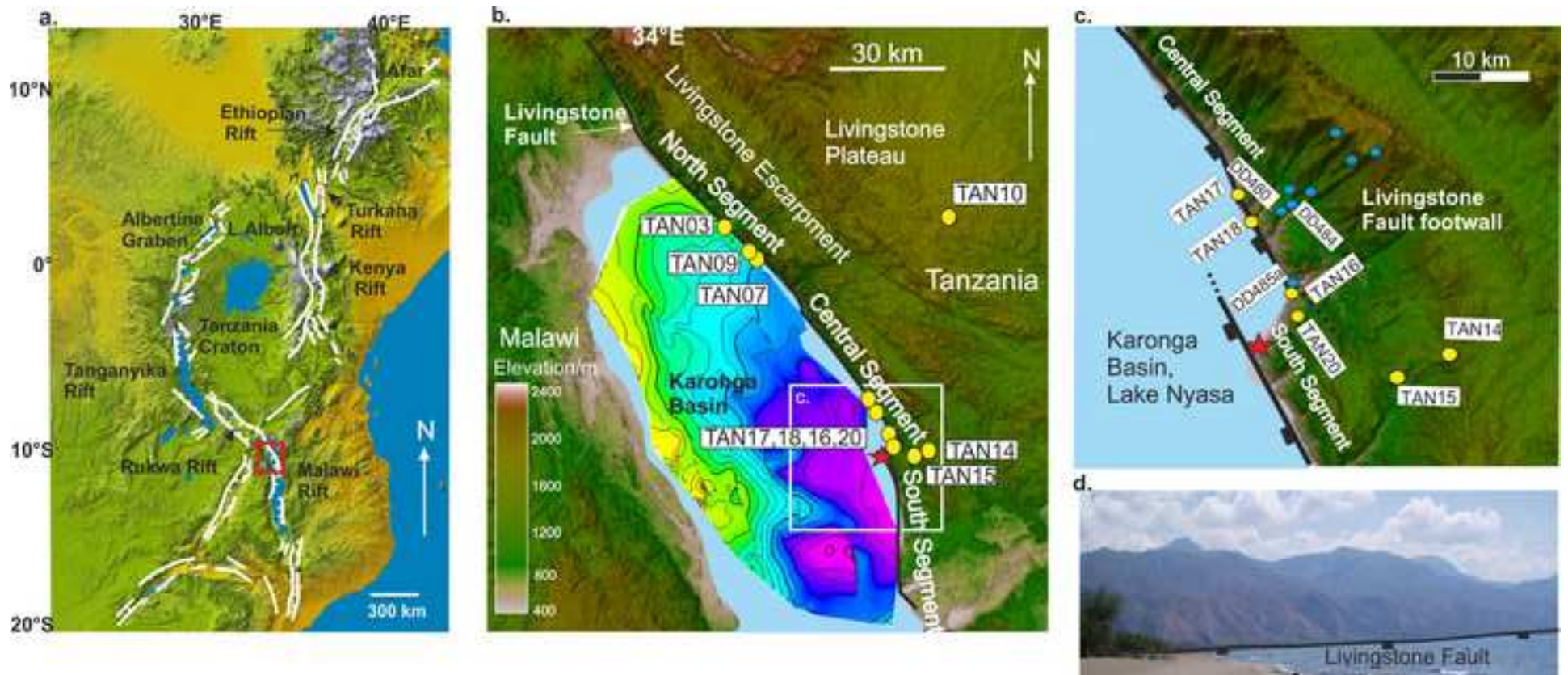


Figure 3 low res
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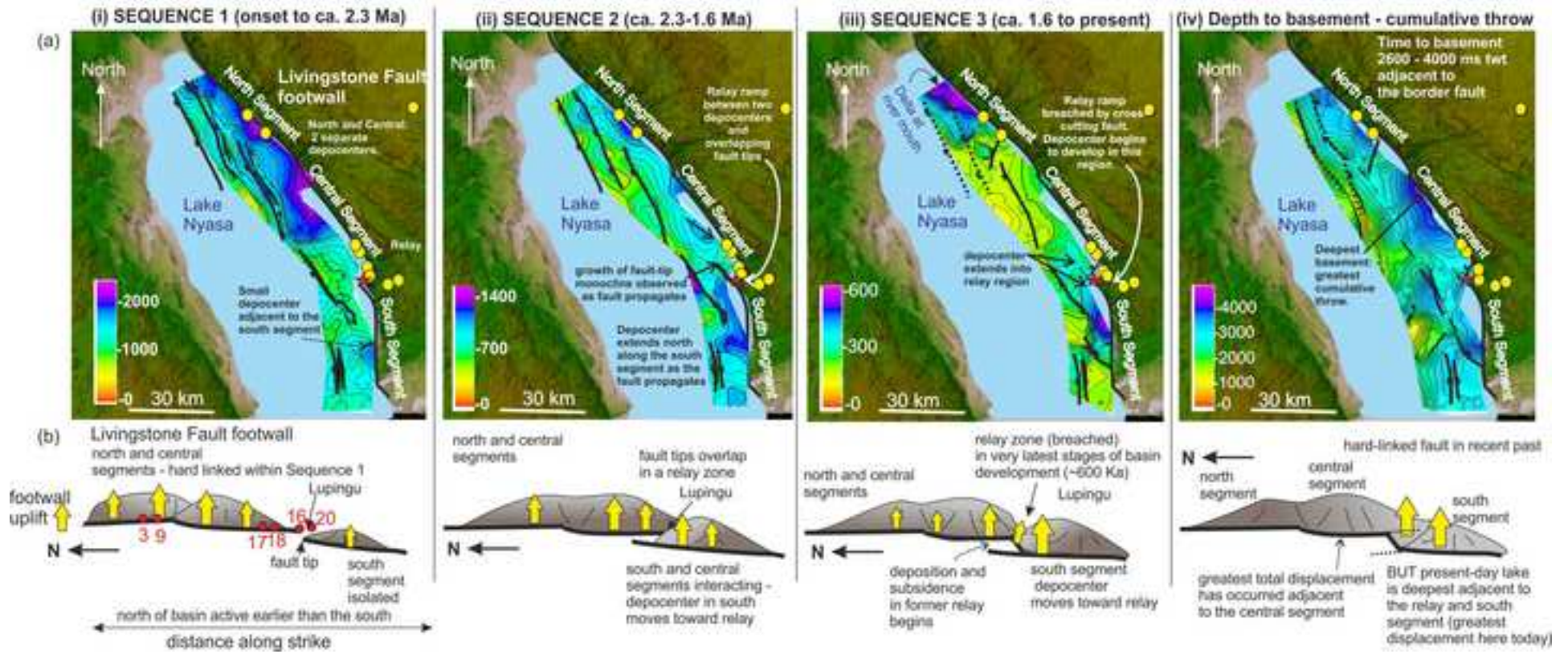


Figure 4 low res
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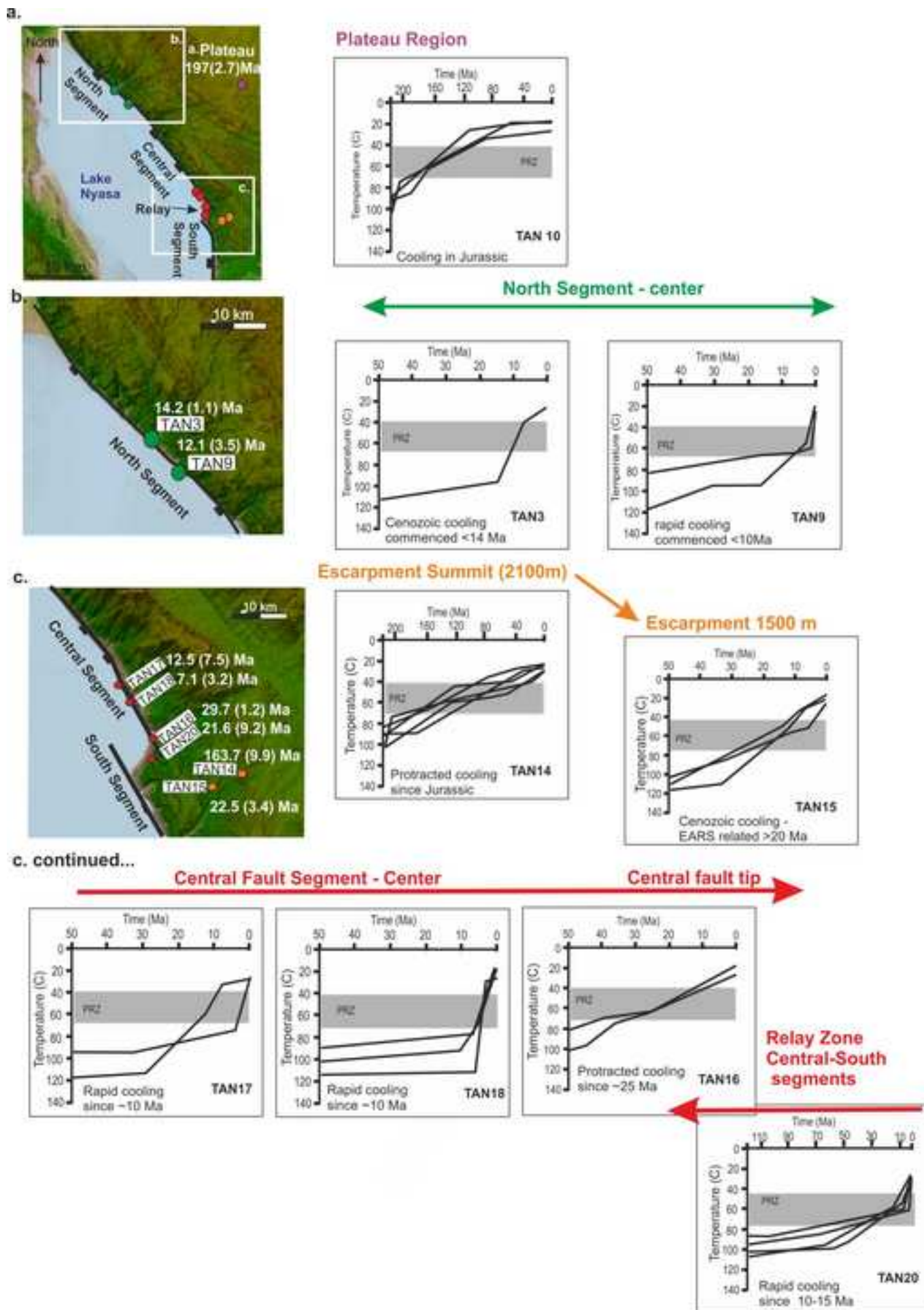


Figure 5 low res
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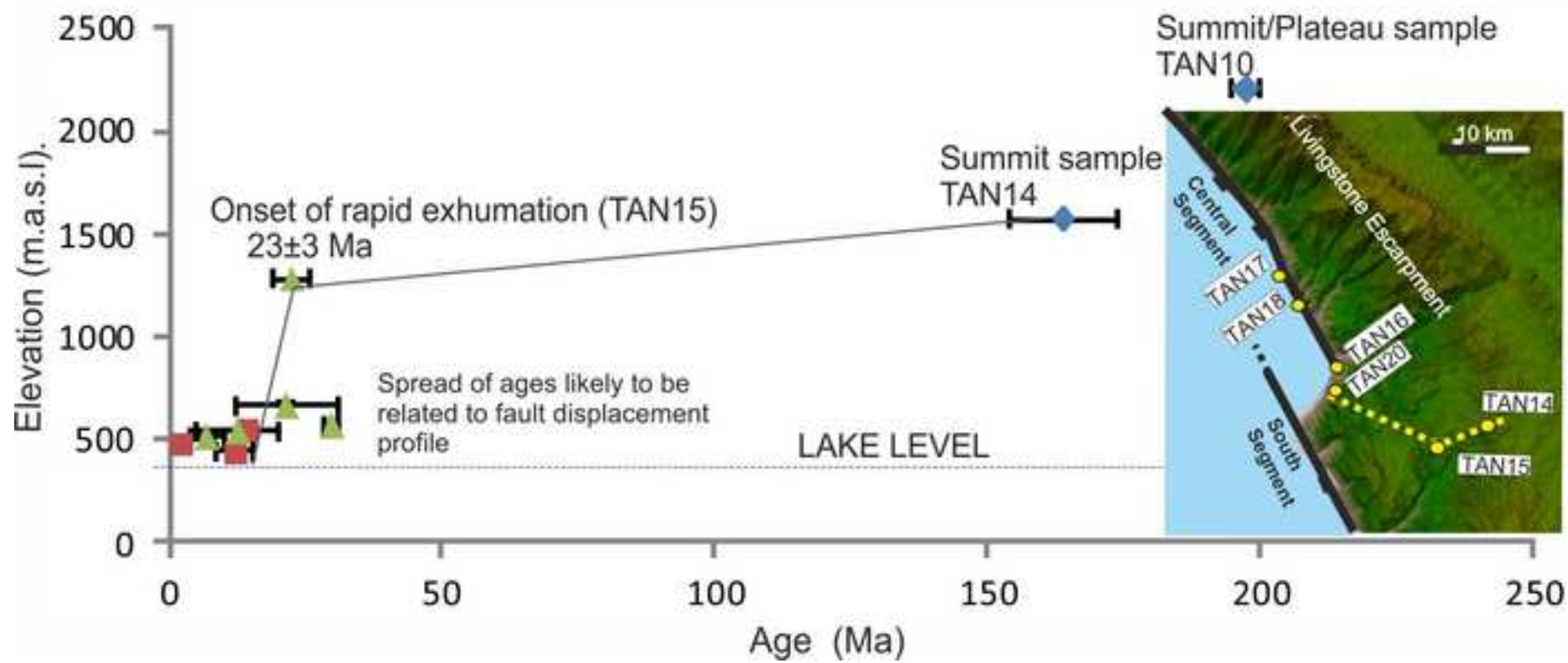


Figure 6 low res

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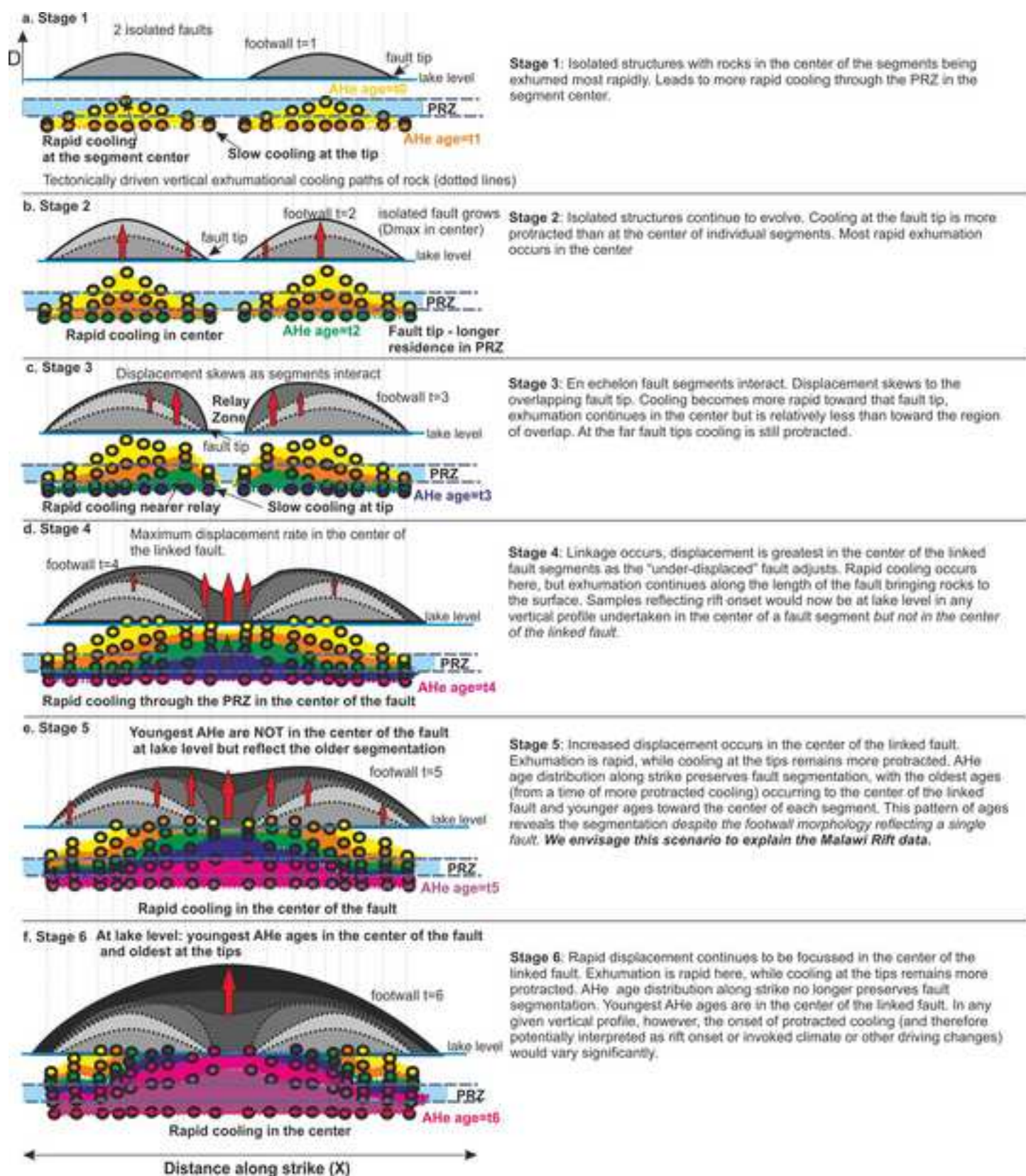


Table 1

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Sample name	Northing	Easting	⁴ He (ccSTP)	²³⁸ U (ng)	²³⁵ U (ng)	²³² Th (ng)	Th/U	error	Uncorr. He age (Ma)	Ft	Corr. He age (Ma)	Error (Ma)	Blank Used
Livingstone summit and plateau.													
TAN 10-1	8942252	684162	6.048E-09	0.215	0.002	0.573	2.7	0.0	140.7	0.71	197.0	4.5	CT DUR
TAN 10-2	8942252	684162	8.320E-09	0.298	0.002	0.576	1.9	0.0	155.9	0.80	195.9	4.4	CT DUR
TAN 10-3	8942252	684162	2.043E-08	0.646	0.005	1.757	2.7	0.0	156.9	0.79	199.5	4.7	CT DUR
TAN 14-1a	8881903	679108	7.858E-09	0.285	0.002	0.868	3.0	0.0	130.8	0.85	154.5	6.9	VU DUR
TAN 14-1b	8881903	679108	4.251E-09	0.105	0.001	0.592	5.6	0.1	141.9	0.86	164.4	7.5	VU DUR
TAN 14-1c	8881903	679108	5.120E-09	0.176	0.001	0.530	3.0	0.0	138.8	0.83	166.8	7.0	VU DUR
TAN 14-2	8881903	679108	1.376E-08	0.633	0.005	1.161	1.8	0.0	123.7	0.82	150.0	6.6	VU DUR
TAN 14-3	8881903	679108	3.957E-09	0.133	0.001	0.453	3.4	0.1	134.5	0.76	176.4	5.4	VU DUR
Livingstone Fault escarpment (North segment)													
TAN 03-A	8940289	626406	7.652E-11	0.029	0.000	0.094	3.3	0.1	12.4	0.87	14.2	0.3	VU DUR
TAN 05	8946770	617979	1.074E-09	0.051	0.000	0.111	2.2	0.0	113.2	0.69	163.6	5.1	VU DUR
TAN 07-A	8931423	634768	6.784E-12	0.056	0.000	0.267	4.8	0.1	0.5	0.67	0.7	0.0	VU DUR
TAN 07-B	8931423	634768	1.609E-11	0.043	0.000	0.162	3.7	0.1	1.6	0.77	2.1	0.1	VU DUR
TAN 07-C	8931423	634768	1.587E-11	0.062	0.000	0.287	4.6	0.1	1.0	0.66	1.5	0.0	VU DUR
TAN 09-A	8933587	632621	3.647E-11	0.030	0.000	0.026	0.9	0.0	8.3	0.74	11.2	0.3	VU DUR
TAN 09-C	8933587	632621	4.195E-11	0.030	0.000	0.016	0.5	0.0	10.1	0.69	14.7	0.5	VU DUR
Livingstone Fault escarpment (North segment)													
TAN 15-A	8880090	676027	1.853E-10	0.073	0.001	0.058	0.8	0.0	17.5	0.82	21.5	0.5	VU DUR
TAN 15-B	8880090	676027	1.714E-10	0.077	0.001	0.041	0.5	0.0	16.2	0.75	21.5	0.6	VU DUR
TAN 15-C	8880090	676027	1.833E-10	0.065	0.000	0.048	0.7	0.0	19.7	0.77	25.6	0.7	VU DUR
TAN 20-A	8885312	669333	7.835E-10	0.227	0.002	0.204	0.9	0.0	23.4	0.77	30.3	0.7	VU DUR
TAN 20-B	8885312	669333	1.405E-09	0.610	0.004	0.344	0.6	0.0	16.7	0.85	19.6	0.4	VU DUR
TAN 20-C	8885312	669333	1.649E-09	0.561	0.004	0.368	0.7	0.0	20.9	0.81	25.7	0.5	VU DUR
TAN 20-D	8885312	669333	5.869E-10	0.295	0.002	0.234	0.8	0.0	13.8	0.77	18.0	0.4	VU DUR
TAN 16-1	8885628	669212	1.041E-09	0.377	0.003	0.076	0.2	0.0	21.7	0.71	30.4	0.8	CT DUR
TAN 16-2	8885628	669212	8.401E-10	0.308	0.002	0.066	0.2	0.0	21.4	0.73	29.2	0.7	CT DUR
TAN 17-A	8892500	664893	2.102E-10	0.081	0.001	0.247	3.1	0.1	12.4	0.77	16.2	0.3	VU DUR
TAN 17-C	8892500	664893	2.896E-11	0.016	0.000	0.067	4.3	0.1	7.6	0.88	8.7	0.3	VU DUR
TAN 18-A	8890311	666454	2.653E-10	0.140	0.001	0.478	3.4	0.1	8.6	0.86	10.0	0.2	VU DUR
TAN 18-B	8890311	666454	8.346E-11	0.068	0.000	0.172	2.5	0.0	6.3	0.83	7.6	0.1	VU DUR
TAN 18-C	8890311	666454	1.157E-10	0.098	0.001	0.419	4.3	0.1	4.8	0.82	5.8	0.1	VU DUR
Standards													
CT DUR			9.567E-09	0.431	0.003	8.492	19.7	0.3	32.4				
CT DUR			5.844E-09	0.270	0.002	5.745	21.3	0.3	29.6				
VUDUR48			4.561E-09	0.172	0.001	3.998	23.3	0.4	33.6				
VUDUR49			3.048E-09	0.123	0.001	2.569	20.8	0.3	34.3				

Table 1: Analytical data for AHe samples along the rift shoulder of the North Basin, Malawi Rift. CT DUR and VU DUR are Durango standards obtained from Ken Farley at Caltec and from Tibor Dunai, Vrije Universiteit respectively. Amp Gneiss = amphibolites gneiss.

Note for Tan 07: He contribution from the blank is significant (15%), however there is sufficient U and Th to include this age in the analyses. The low He contained in the sample is probably due to its young age.

Table 2: Apatite He age and elevation data for samples from the North Basin, Malawi Rift.

Sample	Age (Ma) †	$\pm 2\sigma$ (Ma)	Elevation (m)
<i>Livingstone summit and plateau</i>			
TAN10	197.4	2.7	2194
TAN14	163.7	9.9	1569
<i>Livingstone Fault escarpment (North segment)</i>			
TAN3	14.2*	1.1	550
TAN7	2.1	1.3	489
TAN9	12.1	3.5	450
<i>Livingstone Fault escarpment (Central and South segments)</i>			
TAN15	22.5	3.4	1270
TAN20	21.6	9.2	673
TAN16	29.7	1.2	548
TAN17	12.5	7.5	538
TAN18	7.1	3.2	509

† All ages calculated from weighted average of replicates following correction except those indicated by * where ages were not replicated. The location of samples is shown in Figure 1.

Supplementary material for online publication only

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