

Rift and plume: a discussion on active and passive rifting mechanisms in the Afro-Arabian rift based on synthesis of geophysical data

Ran Issachar^{1,2}, Peter Haas^{1,3}, Nico Augustin³ and Jörg Ebbing¹

¹Institute for Geosciences, Kiel University, Geophysics, Kiel, Deutschland, ²Geological Survey of Israel, Jerusalem, Israel,

³GEOMAR Helmholtz Centre for Ocean Research, Kiel, Deutschland

Correspondence to: Ran Issachar (ranis@gsi.gov.il)

Abstract

The causal relationship between the activity of mantle plumes and continental break-up is still elusive. The Afro-Arabian rift system offers an opportunity to examine these relationships, in which an ongoing continental break-up intersects a large Cenozoic plume-related flood basalt series. In the Afar region, the Gulf of Aden, the Red Sea, and the Main Ethiopian Rift form an R-R-R triple junction, separating the Ethiopian and Yemen Traps by ~600 km. We provide an up-to-date synthesis of the available geophysical and geological data from this region. We map the rift architecture in the intersection region of the rifts and review the spatio-temporal constraints ~~in developing~~ the different features of the plume-rift system.

We infer two spatial constraints in the development of the rifts: (1) **the connection** of the Main Ethiopian Rift to the Gulf of Aden and the Red Sea by its northeastward propagation; (2) the abandonment of an **early tectonic** connection between the Red Sea and the Gulf of Aden. Additionally, chronological **evidence** suggests that regional uplift and flood basalt eruptions ~~sufficiently~~ preceded rifting. By this, we ~~infer~~ a progressive development in which the onset of the triple junction marks a tectonic reorganization and was the last feature to develop after all rift arms were thoroughly ~~developed~~. We argue that the classical active and passive rifting mechanisms cannot simply explain the progressive development of the Afro-Arabian rift and propose a ~~scenario of~~ plume-induced plate rotation that includes an interaction between active and passive mechanisms. In this **scenario**, the arrival of the Afar plume provided a push force that promoted the rotation of Arabia **around a nearby pole**, enabling the rifting and, ultimately, the break-up of Arabia from Africa.

27

Short summary:

We explore the causal relationship between the arrival of the Afar plume and the initiation of the Afro-Arabian rift. We mapped the rift architecture in the triple junction region ~~from~~ geophysical data and reviewed the available geological ~~temporal evidence~~. We ~~infer~~ a progressive development of the plume-rift system and suggest an interaction between active and passive mechanisms in which the plume provided a push-force that changed the kinematics of the associated plates.

1. Introduction

The causal dependency between the eruption of flood basalts and continental break-up is still unclear, although a close occurrence between these two phenomena has been recognized for a long time.

37 Continental flood basalts, often referred to as traps, form large igneous provinces covering huge
38 continental areas (Bryan and Ferrari, 2013; Ernst, 2014). Continental flood basalts are often associated
39 with extensive volcanism during short time intervals, which are brought to the surface by deep-seated
40 mantle plumes (Richards et al., 1989; White and McKenzie, 1995; Koppers et al., 2021), although other
41 mechanisms were also suggested (e.g., Anderson, 1994, 2005). There is evidence for a close temporal and
42 spatial occurrence between the eruption of flood basalts and continental break-up. In particular, when
43 reconstructed back to their original plate tectonic configuration, an R-R-R triple junction is typically found
44 within the flood basalt areas (Morgan, 1971; Burke and Dewey, 1973; Buitert and Torsvik, 2014). Using the
45 geological record to examine the mutual dependency of these processes is challenging. It requires high-
46 precision constraints regarding the temporal and spatial development of the different volcanic and
47 tectonic features, often obscured by the long geological history.

48 The Afar region in the central parts of the Afro-Arabian rift system is recognized as a key locality to examine
49 models of plume-rift association, offering a young and active case study in which plume, regional uplift, R-
50 R-R triple junction, break-up, and oceanic spreading co-exist and are superimposed (Fig. 1). Plume-rift
51 association is mainly explained by either ‘active’ (e.g., Sengör and Burke, 1978) or ‘passive’ (e.g., White
52 and McKenzie, 1989) views, with no interaction between those modes. However, some evidence suggests
53 a more complex effect of plumes on the regional plate kinematics (e.g., Cande and Stegman, 2011). Despite
54 the contrary implications of the ‘active’ and ‘passive’ views, the Afar case study was used as a prime
55 example to support both, and some authors argued that both processes are required to explain the
56 observations (Burke and Dewey, 1973; White and McKenzie, 1989; Courtillot et al., 1999). The discrepancy
57 can be primarily attributed to a lack of accurate geological and geophysical evidence, leading to contrary
58 interpretations.

59 The purpose of this paper is to utilize a synthesis of the available geological and geophysical data from the
60 Afar region and to use it for geodynamic implications in the study area. We first review the evidence
61 regarding the temporal association of the volcanic and rift components of the system. This review is
62 essential because large amounts of new data were collected in recent years, enabling a re-examination of
63 the relationships between the plume and the rifting. We further provide an analysis and interpretation of
64 modern geophysical datasets, including topography, bathymetry, gravity, magnetic anomalies,
65 earthquakes, and volcano distribution. Using these datasets, we map the architecture of the rift margins
66 and axes and infer spatial constraints in developing the rift segments. Finally, we discuss the results in the
67 light of recent models and other case studies in the world, aiming to shed light on the causal relationship
68 between mantle plumes and tectonic processes in the crust.

69 2. Active and passive mechanisms for plume-rift association

70 The existence of deep mantle convection and its interaction with the Earth’s lithosphere was already
71 pointed out by Wilson (1963), and a close occurrence to continental break-up was soon noticed by the
72 abundance of hotspots near many rift junctions (Morgan, 1971) and flood basalt volcanism along passive
73 margins (Richards et al., 1989). Although Morgan (1971) speculated that deep mantle convection has a
74 significant role in accelerating the overlying tectonic plates, it was later realized that slab-pull provides the
75 main driving force for plate motion (Forsyth and Uyeda, 1975). In their landmark paper, Burke and Dewey
76 (1973) presented 45 case studies of rift junctions associated with hot spots. They proposed a model in
77 which plume-associated uplift and volcanism precede and generate the rift arms, initiated from a triple

78 junction within the plume region. Afar was used as a first and prime example, highlighting its importance
79 as a young and active case study; however, they already noted its complexity (Burke and Dewey, 1973).

80 Following these insights, 'active' rifting models were developed to explain plume-rift associations (e.g.,
81 Keen, 1985; Moretti and Froidevaux, 1986; Campbell and Griffiths, 1990; Hill, 1991; White and McKenzie,
82 1995). These models generally propose that rifting can result from a combination of processes derived
83 from the actively rising head of an anomalously hot mantle. These include impinging and eroding the base
84 of the lithosphere, which prompts uplift and decompression melting, which in turn introduces internal
85 extensional forces and ultimately leads to break-up. Accordingly, in this view, regional uplift and volcanism
86 are expected to precede rifting, which would initiate from a triple junction above the mantle plume head
87 (Fig. 2a).

88 Later contributions challenged the active view, arguing that a 'passive' asthenospheric upwelling can also
89 resolve the occurrence of flood basalt near rifts (firstly introduced by White and McKenzie, 1989). In this
90 view, rifting is initiated by the remote stresses, usually along former sutures and weak zones, regardless
91 of underlying plumes. The production of massive volcanism is allowed when the thinned and stretched
92 lithosphere is overlaid by a thermal anomaly in the mantle. The volcanism is generated by decompression
93 melting of the hot asthenospheric mantle, passively rising. As plumes form large areas of higher
94 temperatures in the mantle, massive volcanism is found on Earth's crust close to rifts. Accordingly, in this
95 view, subsidence is a precondition required for magmatism, and there is no particular reason for a triple
96 junction to form within the flood basalts region (Fig. 2b).

97 Although active and passive views have been discussed in the last 50 years, the role of plumes in initiating
98 rifting is still unclear and much debated. Even for well-studied and prime examples of plume-rift
99 association as the Siberian, Parana-Etendeka, Deccan, and Greenland traps, there is no agreement on
100 whether active processes initiated rifting (Geoffroy, 2005; Ivanov et al., 2015; Frizon De Lamotte et al.,
101 2015; Fromm et al., 2015; Mitra et al., 2017). Some authors emphasize the significance of preexisting
102 lithosphere weaknesses along structural inheritance and former sutures (Buiter and Torsvik, 2014; Will
103 and Frimmel, 2018), while others show the potential of plumes to thermally and chemically erode the base
104 of the lithosphere in the weakening process allowing rifting (Sobolev et al., 2011). Additionally, some
105 models demonstrate that mixed active-passive scenarios can better explain observation (Koptev et al.,
106 2018), and even that both mechanisms are needed to explain temporal variations in rifts (Huisman et al.,
107 2001).

108 In addition to the dichotomic views, some evidence implies more complex relationships between plumes
109 and the kinematics of the associated plates (van Hinsbergen et al., 2011; Cande and Stegman, 2011;
110 Chatterjee et al., 2013; Pusok and Stegman, 2020). These studies discuss the role of plumes in changing
111 the relative motions of the overlying plates and suggest that lateral forces, induced by the arrival of the
112 plume head, can add up to the remote stresses, change the plate kinematics and even trigger the
113 formation of new plate boundaries (van Hinsbergen et al., 2021) (Fig. 2c). Thus, in this view the plume is
114 changing the remote stress field, which in-turn allows rifting.

115 3. Geological setting

116 The Afro-Arabian rift system extends from Turkey to Mozambique (McConnell and Baker, 1970) and is the
117 current episode of the Phanerozoic break-up of the East African continental plate (Bosworth, 2015). It

118 contains rifting in the Gulf of Aden, in the Red Sea, and in East Africa. In the center of that system, the
119 Ethiopian northwestern and southeastern plateaus represent an elevated topography with a highest peak
120 of 4,620 m (Ras Dashan) and an average elevation of 2000 m above sea level. This area is part of the so-
121 called African Superswell, a wide region of anomalously high topography comprising East Africa (Lithgow-
122 Bertelloni and Silver, 1998; Corti, 2009). In western Yemen, the Sarawat Mountains are the highest peaks
123 in the Arabian Peninsula, reaching more than 3,000 m, at only 100 km from the shoreline of the Red Sea.
124 The mountains show a typical stair morphology with steep slopes at the western and southern sides, while
125 the eastern side slopes downward more gently.

126 The Gulf of Aden is the most developed rift segment in the Afro-Arabian rift, with a mature and fully
127 developed oceanic spreading center connected to the mid-ocean ridge in the Indian Ocean. Six pairs of
128 magnetic anomalies associated with seafloor spreading are recognized along the Gulf of Aden (Fournier et
129 al., 2010) (Fig. 3). Oblique rifting and high-angle structural inheritance along the Gulf of Aden resulted in
130 multiple ridge segments and fracture zones (i.e., transform faults; Leroy et al., 2013; Autin et al., 2013;
131 Bellahsen et al., 2013; Duclaux et al., 2020).

132 At the northern parts, rifting in the Red Sea is connected by the Dead Sea Fault to the Eurasian collision
133 zone along the Taurus-Zagros Mountains. The Red Sea is experiencing the last stages of break-up and early
134 stages of oceanic accretion. An oceanic spreading center with three pairs of ridge parallel magnetic
135 anomalies is developed in the southern parts of the Red Sea (Schettino et al., 2016) (Fig. 3). However,
136 oceanic crust is probably flooring most of the basin (Augustin et al., 2021).

137 The Main Ethiopian Rift is the northernmost section of the intra-continental rifting in East Africa, splitting
138 the not-yet well-individualized Somali plate from Africa (Chorowicz, 2005). Current rifting in the Main
139 Ethiopian Rift is characterized by a narrow rift valley, in which volcanic and tectonic activities are localized
140 and influenced by oblique rifting conditions (Corti, 2009).

141 ~~The Afar triangle is where the above-mentioned three rift arms meet (Fig. 3). It is considered a geological~~
142 ~~depression as it is an area of low elevation compared to the high Ethiopian plateaus,~~ and thus commonly
143 referred to as the Afar 'depression'. Nevertheless, this term is misleading as the Afar triangle is included
144 within the rifted area and is geologically elevated from the deep bathymetry of the Gulf of Aden and the
145 Red Sea basins. The Afar triangle is mainly floored by Pliocene and younger volcanic rocks, where Miocene
146 volcanic series are exposed along the western margins and at the elevated Danakil block. It comprises
147 many volcanoes that compose axial volcanic ranges (Fig. 2), where the Red Sea side is characterized by
148 transverse volcanic fields and the southern side by central volcanoes (Varet, 2018). Two symmetric
149 magnetic anomalies have been recognized in the Tendaho graben, similar to those observed along
150 spreading centers in the Gulf of Aden (Bridges et al., 2012). These could be associated either with young
151 oceanization or with linear anomalies developed in transitional crust (Ebinger et al., 2017). Structurally,
152 several mega-scale accommodation zones connecting the different rift segments and a triple junction
153 location are recognized at 11.0°N, 41.6°E at the Tendaho-Goba'ad Discontinuity (e.g, Tesfaye et al., 2003)
154 (Fig. 3).

155 4. Temporal constraints

156 4.1. Flood basalts and uplift

157 Vast efforts were made to study the chemistry and chronology of flood basalts in East Africa (see review
158 by Rooney, 2017). Two phases of extensive flood basalt volcanism are associated with plume-lithosphere
159 interaction (Fig. 4). The early phase is mainly confined to southern Ethiopia and northern Kenya. The timing
160 of this event is poorly constrained to 45-35 Ma (George et al., 1998). The second phase of flood basalt
161 eruptions was more voluminous, more widespread, and shorter-lived. Earliest basalts of this phase date
162 back to 34 Ma near Tana Basin, Ethiopia (Prave et al., 2016) and 31 Ma in western Yemen (Peate et al.,
163 2005) (Fig. 4). The traps accumulated very rapidly, in less than 6 Ma (Coulié et al., 2003), and include
164 tholeiitic to alkaline compositions of asthenosphere mantle source (Mattash et al., 2013). Thick sequences
165 of up to 2 km are observed within a widespread region in Ethiopia and Kenya (Bellieni et al., 1981; Wescott
166 et al., 1999; McDougall and Brown, 2009). It is commonly accepted that these flood basalts are of a deep-
167 seated mantle plume origin (Koppers et al., 2021). However, the mechanism is debatable and may involve
168 multiple plume impingements within a broad upwelling zone connected to the African superplume in the
169 lower mantle (Meshesha and Shinjo, 2008) or a single plume-lithosphere interaction (Rooney, 2017).

170 An elevated topography is associated with the eruption of the flood basalts in Ethiopia. The flood basalts
171 are almost exclusively positioned within the elevated regions of the Ethiopian and Somalian plateaus and
172 the Sarawat Mountains in southwest Yemen (Fig. 1). Dynamic topography component supports up to 1 km
173 of present-day elevation of the Ethiopian and Somalian plateaus, confirming the significant contribution
174 of mantle convection to the regional uplift (Gvirtzman et al., 2016). Although the uplift chronology is not
175 easily resolved, recent studies infer it is a long-term feature already present before the emplacement of
176 the flood basalts (Sembroni et al., 2016; Faccenna et al., 2019). Regional uplift is estimated to begin before
177 40 Ma, with maximal uplifts between 12 and 28 Ma, reaching an average elevation of 2500 m (Fig. 4)
178 (Sembroni et al., 2016).

179 4.2. Gulf of Aden

180 The beginning of continental rifting in the Gulf of Aden is only approximately known (Bosworth et al.,
181 2005). Estimates mainly rely on the dating of sedimentary sequences, and no recent data were published.
182 The evidence of rift initiation was summarized by Bosworth et al. (2005). Various sedimentary indications,
183 including onshore outcrops in Yemen (Watchorn et al., 1998) and in Oman (Roger et al., 1989) and offshore
184 wells (Hughes et al., 1991), suggest that rifting in the central and eastern Gulf of Aden began at early to
185 mid-Oligocene, within the Rupelian, i.e., 33.9 - 27.8 Ma. Syn-rift sediments from the central Yemeni
186 margins indicate that rift flank uplift occurred before any significant regional extension. The continental
187 rifting climax is estimated between 20 and 18 Ma (Watchorn et al., 1998). Radiometric dating indicates
188 that the margins became stable already in the Early Miocene (Bosworth et al., 2005), and rift-to-drift
189 transition is interpreted to occur between ~21.1 and ~17.4 Ma (Watchorn et al., 1998). The seafloor
190 spreading center in the Gulf of Aden is developed along most of its length and is connected to the mid-
191 ocean ridge in the Indian Ocean through the Sheba Ridge (Gillard et al., 2021). In the central Gulf of Aden,
192 magnetic isochrons suggest opening rates of ~27 mm/yr prior to 11 Ma, and a slowdown after 11 Ma (Fig.
193 4). Chron 5C (purple stripes in Fig. 3; 16.0 Ma) is present along the Gulf of Aden up to the Shukra al Sheik
194 discontinuity (Fournier et al., 2010). This implies that the spreading center developed rapidly, perhaps
195 instantaneously, in geological time scales, covering a distance of more than 700 km in less than 1.5 Ma.

196 This fast propagation ceased at the Shukra al Sheik discontinuity (Fig. 3). The youngest magnetic isochrons
197 (2A, 2.6 Ma) are recognized up to longitude 43.9°E in the eastern Gulf of Tadjoura, ~150 km west to the
198 Shukra al Sheik discontinuity, indicating that along this segment, the ridge propagated westward at an
199 average rate of ~11 mm/yr, in the last 16 Ma. Within the Gulf of Tadjoura, no direct evidence of oceanic
200 spreading was reported to our best knowledge.

201 4.3. Red Sea

202 ~~It is not certain when~~ continental rifting in the Red Sea ~~began; however,~~ sedimentary sequences suggest
203 ~~it postdates~~ rifting in the Gulf of Aden by a few million years (Bosworth et al., 2005). Independent evidence
204 suggests that rifting had begun simultaneously along the entire Red Sea at late Oligocene-Early Miocene,
205 ~23 Ma (Plaziat et al., 1998; Szymanski et al., 2016; Stockli and Bosworth, 2018; Morag et al., 2019).
206 Magnetic isochrons associated with seafloor spreading are only ~~known from~~ the southern parts of the Red
207 Sea. However, oceanic lithosphere is probably ~~abundant along~~ most of the basin (Augustin et al., 2021).
208 Chron 3 (4.2 Ma) is only present between latitudes 16° and 18°, while chrons 2A (2.6 Ma) and 2 (1.8 Ma)
209 are present up to latitude 22° (Schettino et al., 2016). ~~Evidence for~~ Chron 5 (10 Ma) in the central Red Sea
210 was recently suggested to mark the beginning of seafloor spreading (Okwokwo et al., 2022). Structural
211 reconstructions, geodetic measurements, and magnetic anomalies ~~suggest~~ opening rates of ~11 mm/yr in
212 the central parts of the basin, with an abrupt increase at ~5 Ma (Fig. 4) (Schettino et al., 2018). ~~The~~
213 ~~southern edges of the magnetic chrons suggest that the ridge rapidly propagated southwards, with rates~~
214 ~~of ~30 mm/yr, between chrons 3 (4.2 Ma) and 2A (2.6 Ma).~~ Since 2.6 Ma, the Red Sea ridge has not
215 propagated southward, probably due to the decrease in angular velocity of Danakil relative to Arabia (Fig.
216 3 ; Schettino et al., 2018).

217 4.4. Main Ethiopian Rift

218 Results from many years of extensive fieldwork (see Corti, 2009 for review) suggest a diachronous
219 development of the different segments of the Main Ethiopian Rift. However, there is no agreement
220 regarding the exact timing of events and even the propagation trend of the rift. Reconstructions based on
221 magnetic anomalies from the Southwest Indian ridge suggest an upper limit for the Nubia-Somalia
222 separation at ~19 Ma, including large uncertainties (DeMets and Merkouriev, 2016) (Fig. 4). There are
223 indications that rifting in East Africa started at the Turkana depression in southern Ethiopia (Varet, 2018)
224 and propagated north to Afar (Wolfenden et al., 2004); however, this is still a matter of debate (see figs
225 42-44 in Corti, 2009). Radiometric dating of structural features indicates that extension commenced at ~11
226 Ma within the northern Main Ethiopian Rift (Wolfenden et al., 2004).

227 In summary, regional uplift and flood basalt volcanism in Ethiopia preceded the rifting of the Afro-Arabian
228 rift. The rift arms developed at different times, when rifting in the eastern Gulf of Aden started during the
229 late phases of flood basalt volcanism in Ethiopia. Rifting in the Red Sea and the Main Ethiopian Rift started
230 in a lag of ~5-7 Ma after flood basalt volcanism.

231 5. Data and Methods

232 We used bathymetry and topography data to identify morphotectonic features. To highlight and map the
233 architecture of the margins and axes of the rifts, we applied the Difference of Gaussians method to the
234 topography and the bathymetry grids (Akram et al., 2017). This method allows a fast and accurate edge

235 detection of elevation using active spatial bandpass filtering. We applied luminance coloring to the
236 resulting grid using the open-source image processing software Gimp.org.

237 To study density-related shallow crustal structures, we used the satellite altimetry-derived vertical gravity
238 gradient (VGG) model of Sandwell et al. (2014), offering 1 arc-min resolution at offshore regions. As higher
239 frequencies are intensified in the spectral power of the VGG, its anomalies are more source-localized and
240 shallow-sensitive than free-air anomalies. To enhance the edges associated with the VGG, we applied a
241 linear 11-colors colormap, further applied transparency to the VGG map, and projected it on a shaded
242 relief (Fig. 5a).

243 To study deeper crustal structures and eliminate the topography effect, we used Bouguer gravity anomaly
244 (BGA), derived from the XGM2019 gravity model (Zingerle et al., 2020), calculated with a grid step of 0.1
245 degrees. The XGM2019 is the most updated global gravity model of the ICGEM and is provided in terms of
246 spherical harmonics up to 2159 degrees (Ince et al., 2019; Zingerle et al., 2020). In addition, we applied a
247 linear 240-colors colormap to enhance BGA structures, further applied transparency to the BGA map, and
248 projected it on a shaded relief (Fig. 5b).

249 To better correlate and discriminate crustal structures and rift features, we considered 1913 earthquake
250 locations from the International Seismological Centre catalog with minimum magnitudes above 4 ML,
251 recorded between 1964 and 2019. To better infer recent tectonic and volcanic activity, we further
252 considered the locations of Quaternary onshore volcanoes, from the Global Volcanism Program
253 (Smithsonian Institution) and Google Earth mapping.

254 6. Results

255 6.1. Rift margins

256 The most prominent morphological feature of the rift system is the escarpment along its shoulders. The
257 escarpments mark the rift margin as they distinguish between (1) uplifted pre-rift rocks of the Arabo-
258 Nubian shield or trap basalts sequences and (2) Quaternary arid fluvial sediments or young volcanic
259 sequences, although several continental crustal fragments are present within the Afar Triangle. Thus, the
260 escarpments are very distinctive in the topographical and gravity data. The edge detection analysis of
261 topography and bathymetry data allows us to outline the rift margins (Fig. 6).

262 In the Red Sea, the escarpments are generally continuous with an average rift width of 440 ± 20 km
263 (calculated perpendicular to the Red Sea axis in the study area), and a general increase in rift width from
264 north to south (Fig. 6b). We identify two segments that mark an abrupt change in rift orientation and rift
265 width: (1) Below latitudes 15.5° on the African margin and 18° on the Arabian margin (segment I in Fig. 6),
266 the escarpment deviate from its general parallel to the Red Sea trend, bending towards the Afar region.
267 The escarpment is characterized by seismic activity from that point on the African side, which is also
268 considered the northern point of the western Afar margins (Zwaan et al., 2020a). (2) Below latitudes 12.5°
269 on the African margin and 15° on the Arabian margin (segment II in Fig. 6), we identify another abrupt
270 change, both in the orientation and the width of the rift. That point on the African margin is the
271 intersection of the Tendaho-Goba'ad Discontinuity with the Western Afar Margins (Tesfaye et al., 2003).
272 We note that these changes are noticeable and similar on the African and Arabian sides.

273 In the Gulf of Aden, the escarpments generally follow the trend of the basin. In the western parts, the
274 escarpments are less straight and less continuous than those of the Red Sea and generally reflect the
275 sinistral basin structures. This morphology is well explained by oblique rifting along the Gulf of Aden (Leroy
276 et al., 2013). The average rift width in the study area is 470 ± 45 km (calculated rift-perpendicular), with a
277 general eastward increase (Fig. 6b). We recognize an abrupt change in rift width along three lines (III-V in
278 Fig. 6), which are associated with fracture zones. Along the Somalian margin, prominent sinistral offsets
279 are recognized along lines III and V. This escarpment segment is a morphological continuation of the
280 Tendaho-Goba'ad Discontinuity lineament, and is also prominent in the VGG map (Fig. 5a).

281 Although recognizable in the processed topography map, the rift shoulders are less sharp in the Main
282 Ethiopian Rift (Fig. 6a). They are prominent in the gravity data as they are associated with VGG and BGA
283 highs (see profile A in Fig. 9). In the Afar region, the margins show a funnel shape (Fig. 6a). The distance
284 between the Somalian and Ethiopian escarpments is steadily and monotonically increasing from the Main
285 Ethiopian Rift to the Tendaho-Goba'ad Discontinuity (Fig. 6b), suggesting that this segment is intact and
286 non-disturbed by the other arms of the rift system.

287 In summary, the rift margins of the Red Sea and the Gulf of Aden are interrupted by the proximity to the
288 Afar region, whereas the margins of the Main Ethiopian Rift smoothly funnel into the Afar region.

289 6.2. Rift axes

290 Along the Red Sea and the Gulf of Aden basins, the rift axes are distinctively characterized by deep and
291 sharp bathymetric troughs, VGG lows, BGA highs, and intense seismic activity. However, with the proximity
292 to the Afar region, the rift axes change their characteristics.

293 The rift axis along the Red Sea is outlined by a deep and wide axial trough that ends at latitude 14.5° ,
294 approximately 400 km from the triple junction (Fig. 7a). South of latitude 14.5° , we find geophysical
295 evidence that the rift axis is bent, entering the Afar region at the Bay of Beylul (latitude 13.3°). (1) The VGG
296 signature of the Red Sea axis, with highs along the walls of the axial trough and a low above the center
297 (Fig. 7b and profile B). (2) A trail of volcanic islands follows its path (Hanish-Zukur Islands; Fig. 3), and the
298 alignments of volcanic cones and vents on the islands are orthogonal to the trail of the islands (Mitchell
299 and Bosworth, (in press); Gass et al., 1973). (3) A general trend of recent onshore magmatism meets this
300 line at the Bay of Beylul (Fig. 3). However, major fault sets are not observed in the onshore area of Beylul
301 (Rime et al., 2023). (4) This line best fits GPS-based rigid block model (Viltres et al., 2020), and is supported
302 by the fact that the rotation of Danakil relative to Arabia stopped around $t \sim 0.3$ Ma (following Schettino et
303 al., 2018 and personal communication). In addition to this bent segment, a typical gravity signature of the
304 rift axis with a central BGA high and VGG picks to its side, is also recognized along the connection of the
305 Red Sea with the Gulf of Aden at Bab al Mandab Strait (latitudes 13.2° to 12.3° ; Fig. 7 profile CC').
306 Nevertheless, this segment is not an active rift axis as no earthquake, volcanic or bathymetrical expression
307 is associated with it, however, diluted activity is also understood by the low and oblique velocity of Arabia
308 in this area (Fig. 3).

309 In the Gulf of Aden, there is also a distinct change in the rift axis characteristics, approximately 400 km
310 from the triple junction (Fig. 8). Up to the Shukra al Sheik discontinuity, the Gulf of Aden is a deep basin,
311 reaching depths of more than 1,000 m only a few kilometers from the shore, and has a fragmented axial
312 trough, offset by oblique left-lateral transform faults. West to the Shukra al Sheik discontinuity, the basin
313 is shallow, and the axial trough is very distinct, characterized by deep and sharp morphology. This ~ 400
314 km long curved axis segment impales the Afar triangle at the Gulf of Tadjoura (Djibouti). This axial segment

315 has a distinct gravity signature and is characterized by intensive seismic activity, perhaps the most
316 intensive in the rift system, with over 1,000 recorded events with magnitudes above 4ML (ISC catalog).

317 In the Main Ethiopian Rift, there are no abrupt changes in the characteristics of the rift valley with the
318 proximity to the Afar triangle (Fig. 9). Instead, the rift valley goes through an elevated dome peaking
319 approximately 400 km from the triple junction (Fig. 9a). The along-strike profile (profile B in Fig. 9) shows
320 that the rift valley reaches altitudes of more than 2,000 m and is associated with a BGA low.

321 In the Afar triangle, the morphology indicates several axial segments, which are also distinctive in the VGG
322 map (Fig. 10). We recognize axial trends in two distinguished and geographically separated regions: (1)
323 southwest to the Tendaho-Goba'ad Discontinuity, a NE trending valley continues the trend of the Main
324 Ethiopian Rift, characterized by distinct central volcanoes along with an axial depression. (2) Northeast to
325 the Tendaho-Goba'ad Discontinuity, ~~typical rift axial morphologies~~, composed of NW trending short
326 segments along volcanic ranges, are abundant over a 200 km wide zone. Hence, the Afar depression is
327 divided into two morphological regions, in terms of axial trends, parallel to the Main Ethiopian Rift trending
328 region and the Red Sea trending region.

329 In summary, with the proximity to the Afar depression, the rift axes of the Red Sea and the Gulf Aden are
330 not persistent and drastically change their characteristics ~400 km from the triple junction. In contrast,
331 the axis of the Main Ethiopian Rift is consistent, keeping its trend and characteristics up to the triple
332 junction point.

333 7. Discussion

334 7.1. The architecture of the intersection region

335 The Afar triangle is the intersection region of three rift arms: the Gulf of Aden, the Red Sea, and the Main
336 Ethiopian Rift. Far from the intersection region, the axes and margins of these rifts follow a general parallel
337 trend, suggesting that rigid plate tectonics of the Nubian, Arabian, and Somalian plates controlled their
338 structural development (Garfunkel and Beyth, 2006; Reilinger et al., 2006; Reilinger and McClusky, 2011;
339 Schettino et al., 2018). Within the Afar triangle, southwest to the Tendaho-Goba'ad discontinuity, the rift
340 margins are continuous and smooth, and the axial volcanic range generally continues the trend of the axial
341 valley of the Main Ethiopian Rift, reflecting a sub-perpendicular extension in accordance with the Nubia –
342 Somalia kinematics, and thus, could be regarded as a rigid plate boundary. However, the architecture of
343 the intersection region northeast of the Tendaho-Goba'ad discontinuity is more complex and is not simply
344 resolved by rigid plate kinematics (Garfunkel and Beyth, 2006).

345 Fig. 11 summarizes the rift margins and the axial segments mapped in this study. The rift axes of the Gulf
346 of Aden and the Red Sea abruptly change their characteristics, particularly their trends, with the proximity
347 to the Afar region. Around ~400 km from the triple junction, the Gulf of Aden and the Red Sea axes deviate
348 from their basin parallel trend, bending towards the third and younger arm of the Main Ethiopian Rift.
349 Within the Afar triangle, northeast of the Tendaho-Goba'ad discontinuity, the margins are fragmented,
350 and there are multiple, short, and sub-parallel axial segments.

351 In our study, the term "axial segments" inferred is not simply correlated with rift axes, as the geology in
352 this region is quite complex, including several fault and transfer zones, and, exposing pre-rift rock
353 sequences. However, the axial segments mapped in this study in the continental area northeast to the

354 Tendaho-Goba'ad discontinuity is somewhat correlative with rift axes that had been suggested based on
355 field observations (e.g., Rime et al., 2023). Axial segments are generally sub-parallel to the Red Sea axis
356 (Zwaan et al., 2020b), which led authors to suggest that this region reflects an evolving discontinuity of
357 the oceanic spreading center in the Red Sea (e.g. Tazieff et al., 1972; Bosworth et al., 2005). Although
358 several focal solutions indicated dextral strike-slip motions in this area, we don't find other evidence for a
359 typical first-order transform connection between the ridge in the Red Sea and the continuation of the
360 northern Afar axial segments, offshore Gulf of Zula. Magnetic stripes in the Red Sea are observed at more
361 than 200 km south of the Gulf of Zula region (Fig. 12), and the volcanic ridge in the southern Red Sea is
362 very active (Eyles et al., 2018). Although earthquake clusters at latitude 16.5° indicate strike-slip solutions,
363 supporting a structural connection to the Red Sea axis, these are abundant throughout the study area
364 (Hofstetter and Beyth, 2003). Alternatively, it is possible to regard the jump between the Red Sea ridge to
365 the axial segments in northeastern Afar as a non-transform discontinuity. However, second-order
366 discontinuities are usually characterized by <30 km offsets, and here the jump is ~200 km (Macdonald et
367 al., 1984; Carbotte et al., 2016). Thus, we find no circumstantial evidence to regard the axial volcanism in
368 the Afar depression as part of the development of the Red Sea spreading center. This conclusion agrees
369 with the study of Rime et al. (2023), which discusses the geological evidence from Afar.

370 Our analysis highlights that the area northeast to the Tendaho-Goba'ad discontinuity is characterized by
371 diffuse deformation, reflecting a rugged connection of the Red Sea and the Gulf of Aden arms to the Main
372 Ethiopian Rift. Kinematic studies support this view, indicating that microplate rotations and diffuse
373 boundaries significantly influence the structural development of this region. A recent model based on GPS
374 observations (Viltres et al., 2020) reveals a diffuse character of the Danakil - Nubia boundary with inter-
375 rifting deformation over more than 100 km wide zone. The Danakil microplate extends to the Hanish-Zukur
376 Islands at its southern edge (~13.8°N) with no precise/sharp boundary. The Danakil microplate is rotating
377 counterclockwise (Manighetti et al., 2001), while the Ali-Sabieh block, south of the Gulf of Tadjoura, is
378 rotating clockwise (Audin et al., 2004), described as a "saloon-doors" mode of opening (Kidane, 2016).

379 Observations and analog models indicate that strain in Afar is localized in distinct rift segments, which are
380 spread within a broad zone of interaction of the associated plates (Keir et al., 2011; Pagli et al., 2014, 2018;
381 Doubre et al., 2017; Maestrelli et al., 2022). Hence, the architecture of the intersection region of the rift
382 arms discloses a ~150,000 km² complex region, in which diffuse boundaries and microplate rotations link
383 the three rift arms (Fig. 11). Accordingly, a genuinely single triple junction point, in the sense of a three-
384 rift arms intersection point, cannot be specified for this system, and multiple triple junctions could be
385 considered (e.g., see tectonic models in Viltres et al., 2020). The difficulty of defining sharp plate
386 boundaries within Afar was discussed in many works (e.g., Barrberi and Varet, 1977 and references
387 therein). Nevertheless, we agree that the intersection point of the Ethiopian rift valley and the Tendaho-
388 Goba'ad Discontinuity could be regarded as the 'main' junction point of the rift system, as the deformation
389 characteristics are most distinctively changed there (Tesfaye et al., 2003).

390 7.2. Spatial constraints in the development of the plume-rift system

391 The architecture of the Afar region allows us to draw two spatial constraints in the development of the
392 plume-rift system:

393 (1) The first is the connection of the Main Ethiopian Rift to the Gulf of Aden - Red Sea rifts by a
394 northeastward propagation. Since the divergence between Nubia-Somalia is sub-vertical to the strike of
395 the northern Main Ethiopian Rift, resolving its propagation direction is quite intangible and conversed

396 (Tesfaye et al., 2003; Wolfenden et al., 2004; Bonini et al., 2005; Keranen and Klemperer, 2008; Abebe et
397 al., 2010). The margins of southeast Afar show symmetric, continuous, and smooth curved trends, from
398 the elevated regions of the Main Ethiopian Rift to the Tendaho-Goba'ad Discontinuity (Fig. 6). With respect
399 to the northeastward trend of the Main Ethiopian rift, the Somalian margin is curved clockwise, like the
400 Ali-Sabieh sense of rotation (Kidane, 2016), whereas, the Ethiopian margin is curved counterclockwise, like
401 the Danakil sense of rotation (Schult, 1974). This architecture could be understood in terms of fracture
402 mechanics by reorientating a propagating fracture near a pre-existing fracture. Strain analysis indicates
403 that a propagating fracture would curve parallel to the pre-existing fracture under a tensional stress field
404 due to free surface boundary conditions induced by the open pre-existing fracture (Dyer, 1988). Thus, this
405 macro scale architecture may express a smooth linkage of the Main Ethiopian Rift to the pre-existing Gulf
406 of Aden-Red Sea rifts by a northeastward propagation. Hence, this implies that a triple junction formed at
407 a late stage, when all three arms were already significantly developed. This conclusion agrees with
408 structural geochronology within the northern Main Ethiopian Rift, showing that extension in the northern
409 Main Ethiopian rift commenced at 11 Ma (Wolfenden et al., 2004).

410 (2) The second spatial constraint is abandoning an early tectonic connection between the Red Sea and the
411 Gulf of Aden through the Bab al-Mandab Strait. As the VGG and neovolcanic activity indicate that the Red
412 Sea axis currently enters Afar at the Bay of Beylul (see section 6.2), we find arguments for an earlier
413 tectonic connection between the Red Sea and the Gulf of Aden through Bab al-Mandab Strait: (i) Below
414 latitude 13.2° and up to the connection to the Gulf of Aden (at latitude 12.3°), the gravity data shows
415 typical rift axis characteristics, with BGA high and VGG picks to its side (Fig. 7 and Fig. 8; see section 6.2).
416 (ii) The submarine channel north to the Hanish Island (latitude 13.4°) shows no association with modern
417 water currents and may be explained by subsurface rift structures (Mitchell and Sofianos, 2018). (iii) This
418 is the straight continuation of the trend of the Red Sea axis, along which the basins are curvly connected
419 (Fig. 1). Thus, it is reasonable that it was also the tectonic connection in the early stages of rift
420 development. Likewise, reconstructions suggest that the Danakil microplate started to rotate in the Middle
421 Miocene (~10 Ma), when Arabia was already separated from Africa (Collet et al., 2000; Schettino et al.,
422 2016; Rime et al., 2023). Those reconstructions show that until that time, the divergence was focused
423 along the seaway at the southernmost Red Sea. This suggests that the present deviation from the basin
424 parallel trend of the rift axes at the tip of the Gulf of Aden and the Red Sea marks a tectonic reorganization
425 in this region.

426 Adopting the fracture propagation analog postulated here for the northeastward propagation of the Main
427 Ethiopian Rift, it follows that the abandonment of the tectonic connection between the Red Sea and the
428 Gulf of Aden happens as a response to the new stress conditions in Afar. Rime et al. (2023) suggest that
429 the deposition of lacustrine sediments in Afar (Chorora Fm) marks the development of the Main Ethiopian
430 Rift in Afar. They point out that these sediments were deposited roughly at the same time to the
431 individualization of the Danakil Block, and thus to the reduction in the tectonic activity of the southernmost
432 Red Sea rift.

433 These two spatial constraints indicate that the onset of the triple junction happened at a late stage when
434 the three rift arms were already developed and the Red Sea was tectonically connected to the Gulf of
435 Aden, far (~250 km) from the present-day triple junction (Fig. 13). The onset of the triple junction marks a
436 tectonic reorganization and microplate formation. As a result, the Gulf of Aden and the Red Sea arms are
437 not smoothly connected to the Main Ethiopian Rift, and a vast area of diffuse and complex deformation
438 developed within the intersection region.

439 *7.3. Mechanisms for plume-rift association*

440 The temporal constraints regarding the development of the plume-rift features, summarized in section 4,
441 together with the two spatial constraints inferred in this study, allow us to examine the causal relationship
442 between the activity of the Afar plume and rifting. Our insights suggest that neither ‘active’ nor ‘passive’
443 rifting mechanisms are solely consistent with **the observation**. Passive rifting models fail to explain the
444 plume-rift association mainly because the flood basalt volcanism cannot be attributed to passively rising
445 asthenospheric mantle beneath a stretched and thinned lithosphere, as dynamic uplift in Ethiopia ~~was~~
446 ~~shown to be~~ a long-lasting process, ~~prior to~~ flood basalt volcanism (Sembroni et al., 2016). Hence, rifting
447 and associated subsidence are subsequent to flood basalt volcanism (Fig. 4). **The estimations of ~1 km**
448 **elevation before flood basalts** (Fig. 4) coincide with active plume-head predictions (Campbell and Griffiths,
449 1990). Moreover, the passive model does not explain why a triple junction is located within the flood
450 basalts area, as rifting in the Red Sea and Gulf of Aden are at an oblique angle to the former sutures (Buiter
451 and Torsvik, 2014).

452 On the other hand, active models are not in line with the progressive development of the rifts, mainly
453 because the flood basalts region cannot be considered a center or a nucleus, from which rift arms spread,
454 as expected in an actively generated triple junction. Numerous studies noted that the tectonic
455 development of the Afar region is not compatible with a simplified model of rift arms that simultaneously
456 spread away from a triple junction (see Section 5.2 in Rime et al., 2023 for a review). The **inset of a triple**
457 **junction** was the last feature to develop in the system, by the propagation of the Main Ethiopian Rift
458 towards Afar, followed by a tectonic reorganization including the abandonment of a former tectonic
459 connection between the Red Sea and the Gulf of Aden. By this time, the rift arms had already developed,
460 and the break-up had already been accomplished ~~between Africa and Arabia~~. This tectonic reorganization
461 cannot be attributed to the development of gravitational ~~potential~~ by the plume head (Hill, 1991), as it
462 occurred **millions of years after** flood basalts magmatism. That rules out the possibility that the arrival of
463 the Afar plume **generated the onset** of the triple junction, as more than 20 Ma separate these events and
464 the rift arms did not spread from the plume region.

465 We propose a scenario in which rifting was triggered by a plume-induced plate rotation (Fig. 2c). Numerical
466 simulations suggest that horizontal asthenospheric flows due to the arrival of a plume head at the base of
467 the lithosphere induce a plume-push force that can accelerate plates by several cm yr^{-1} (van Hinsbergen
468 et al., 2011, 2021; Pusok and Stegman, 2020). In this scenario, flood basalt volcanism would be
469 synchronous to an abrupt plate speed-up and thus to new remote stress conditions. In the case of the
470 Indian plate, at least two episodes of massive flood basalt volcanism, Morondava LIP (~94 Ma) and Deccan
471 traps (67 Ma), are associated with plume-derived plate acceleration, and a drastic change in the tectonic
472 framework (van Hinsbergen et al., 2011, 2021; Cande and Stegman, 2011; Pusok and Stegman, 2020).
473 Further, **torque balance modeling** suggests that horizontal plume-push can force a significant plate
474 rotation and, consequently, initiate new plate boundaries (van Hinsbergen et al., 2021).

475 In the Afro-Arabian rift, indeed new plate boundaries formed after the arrival of the large Afar plume and
476 a significant plate rotation of Arabia around a nearby pole characterizes the Arabian continent (Joffe and
477 Garfunkel, 1987; Viltres et al., 2022). Magnetic anomalies and structural reconstructions suggest that the
478 rotation around a nearby pole already characterized Arabia since the Oligocene (Fournier et al., 2010;
479 Schettino et al., 2018). Additionally, the beginning of intensive volcanism in the north-western Arabian
480 plate (Harrat Ash Shaam) at Late Oligocene (Ilani et al., 2001), **reflects a change in mantle-crust interaction**
481 and intracontinental extension within the Arabian plate, adjacent to the arrival of Afar plume (Garfunkel,

482 1989). In the Harrat Ash Shaam volcanic field, diking directions from Miocene to recent ages record the
483 rotation of Arabia (Giannerini et al., 1988), suggesting that already during the first stages of volcanism the
484 Arabian plate was rotating around a nearby pole.

485 The arrival of the Afar plume was also accompanied by a slowdown of Africa (Le Pichon and Gaulier, 1988).
486 By this time, Africa collided with Eurasia in the west, explaining its slowdown (Jolivet and Faccenna, 2000)
487 and increased intraplate volcanism (Burke, 1996). However, this collision of Africa and Eurasia cannot
488 simply resolve the change in the rotation of Arabia as the Arabian continent collided with Eurasia not
489 earlier than ~18 Ma (Su and Zhou, 2020), although some authors suggested that asymmetrical along-
490 trench entrance of continental material could lead to an intraplate extension similar to those that
491 generated the Africa-Arabia break-up (Bellahsen et al., 2003). Faccenna et al. (2013) already showed that
492 plume-push from the Afar area resolves the present-day plate kinematics in the Middle East, particularly
493 the anti-clockwise toroidal pattern of the Arabia–Anatolia–Aegean system. The importance of active
494 upwelling in Afar to lateral mantle flow below Arabia is also illustrated by shear-wave splitting, indicating
495 a general N-S anisotropy in the mantle (Qaysi et al., 2018). Stamps et al. (2014) calculated the current
496 driving forces for the Nubia-Somalia divergence and found that gravitational potential energy is the most
497 significant force, stronger by an **order of magnitude** than forces from basal shear tractions of mantle
498 convection. They point out that the gravitational potential energy is sufficient to sustain present-day rifting
499 in East Africa but not to initiate rupture of continental lithosphere. In the case of the Arabian plate, basal
500 shear tractions are expected to be higher due to the orientation of northward-directed mantle flow
501 (Faccenna et al., 2013).

502 If ~~the Afar plume~~ induced the rotation of Arabia around a nearby pole, **then it is understood how the Gulf**
503 **of Aden and the Red Sea rifts developed after a regional uplift and flood basalt volcanism but still**
504 **geometrically developed by the new regional stress field and structural inheritance** (Autin et al., 2013;
505 Bosworth and Stockli, 2016). It also explains why the ~~trace of the~~ rifts intersect within the plume region as
506 the lithosphere in this region was weakened by the hot plume material (François et al., 2018). Finally, it
507 explains the delayed development of the Main Ethiopian Rift and the late ~~onset~~ of the Afar triple junction
508 by its northwestward propagation, as these were controlled by the slower kinematics of the Somalian plate
509 rather than dynamic forces. In this ~~manner~~, ‘active’ and ‘passive’ mechanisms are coupled and have
510 positive feedback, allowing a close occurrence of flood basalt volcanism and continental break-up,
511 alongside a ~~passive style of~~ rifting.

512 8. Summary and Conclusions

513 We reviewed the ~~geologic setting of the~~ Afro-Arabian rift, **in which vast regions of flood basalts and**
514 **ongoing continental break-up are superimposed, aiming to infer a causal relationship between the activity**
515 **of the deep-seated Afar plume and crustal break-up.** We explored the ~~intersection region where~~ the Gulf
516 of Aden, the Red Sea, and the Main Ethiopian Rift ~~form an R-R-R triple junction,~~ separating the large
517 Cenozoic plume-related flood basalt series in Ethiopia and Yemen. ~~We provide a new~~ synthesis and
518 interpretation of ~~modern geophysical datasets, including~~ topography, bathymetry, gravity, magnetic
519 anomalies, earthquakes, and volcano distribution, ~~to map~~ the margins and axes of the rift arms.

520 ~~We highlight key differences in~~ the terminations of the Gulf of Aden and the Red Sea arms, ~~which~~ are rough
521 and irregular, ~~versus~~ the symmetric, continuous, and smooth architecture of the Main Ethiopian Rift. The
522 ~~architecture of the intersection regions~~ allows us to ~~infer~~ two ~~tempo-spatial~~ constraints ~~in~~ the

523 development of the rifts: (1) the connection of the Main Ethiopian Rift to the Gulf of Aden and to the Red
524 Sea by its northeastward propagation, and, (2) the abandonment of an **early tectonic** connection between
525 the Red Sea and the Gulf of Aden. These suggest a progressive development of ~~the~~ intersection area,
526 ~~including a broad region of diffuse deformation and~~ **recent tectonic reorganization**. The **onset** of the triple
527 junction was the last feature to develop in the plume-rift system after all rift arms were sufficiently
528 **developed** and the break-up was accomplished.

529 This progressive development does not align with the classic active rifting model, which predicts a plume-
530 generated triple junction at the locus of the rift, from which the rifts develop. Nevertheless, the classic
531 passive rifting model fails to explain the chronological evidence, as flood basalts probably erupted on
532 elevated topography before rifting started. We discuss a scenario of plume-induced plate rotation in which
533 the arrival of the Afar plume triggered the rotation of Arabia around a nearby pole, ~~and demonstrate that~~
534 ~~the rotation of Arabia around a nearby pole~~ characterizes the system since the Oligocene. We **suggest**
535 that this scenario better explains the progressive development of the plume-rift system in the Afro-Arabian rift.

536 9. Data availability

537 The bathymetry and topography data used in this study was retrieved from GEBCO Compilation Group
538 (2021), available at https://www.gebco.net/data_and_products/gridded_bathymetry_data/#area.

539 The VGG data used in this study is available at https://topex.ucsd.edu/grav_outreach/.

540 The BGA data used in this study is available at <http://icgem.gfz-potsdam.de/calgrid>; model XGM2019e-
541 2159, 'gravity_anomaly_bg'.

542 Earthquake data was retrieved from the International Seismological Centre (2020), On-line Bulletin,
543 <https://doi.org/10.31905/D808B830>.

544 Quaternary onshore volcano locations were retrieved from the Global Volcanism Program, Smithsonian
545 Institution, available at https://volcano.si.edu/volcanolist_holocene.cfm.

546 Magnetic anomalies data is available at

547 [https://figshare.com/articles/dataset/Transcurrent_Regimes_During_Rotational_Rifting_New_Insights_f
548 rom_Magnetic_Anomalies_in_the_Red_Sea/14743272](https://figshare.com/articles/dataset/Transcurrent_Regimes_During_Rotational_Rifting_New_Insights_from_Magnetic_Anomalies_in_the_Red_Sea/14743272).

549 10. Author contribution

550 RI carried out the study and wrote and revised the original draft of this paper. PH and NA provided
551 conceptual assistance, helped in writing and reviewed the manuscript. JE mentored the study, took care
552 of administration, and reviewed the manuscript.

553 11. Competing interests

554 The contact author has declared that neither of the authors has any competing interests.

555 12. Acknowledgments

556 This work was supported by the grants from Minerva Fellowship to R. I. We thank Neil Mitchell and
557 Valentin Rime for their helpful discussion throughout the open discussion process. We wish to thank
558 Antonio Schettino and Derek Keir for their review which helped improving the manuscript.

559 13. Figure captions

560 **Fig. 1.** Elevation map of the study area, showing the general plate tectonic configuration (from USGS and
561 from Viltres et al. (2020) in the Afar region) and Cenozoic volcanics (modified from Varet, 1978; Davison
562 et al., 1994; Beyene and Abdelsalam, 2005; Bosworth and Stockli, 2016) Black arrows indicate GPS
563 velocities in respect to Nubia (modified from Reilinger et al., 2006).

564 **Fig. 2.** Schematic mechanisms for plume-rift association in the Afro-Arabian rift. (a) Active mechanism, in
565 which rifting results from the actively rising head of the Afar plume. In this mechanism impinging and
566 eroding the base of the lithosphere prompt uplift and decompression melting and flood basalts volcanism.
567 These introduce internal extensional forces and ultimately lead to break-up. (b) Passive mechanism, in
568 which rifting is initiated solely by the remote stresses, regardless of underlying Afar plume. In this
569 mechanism the production of massive volcanism is allowed when the thinned and stretched lithosphere
570 is underlaid by the thermal anomaly in the mantle. Flood basalts volcanism is generated by passively rising
571 decompression melting of hot asthenospheric mantle. (c) Plume-induced plate rotation, in which lateral
572 forces, induced by the arrival of the Afar plume head, add up to the remote stresses to change the plate
573 kinematics. In this mechanism flood basalts volcanism is actively controlled, however, rifting is triggered
574 by the new plate kinematics.

575 **Fig. 3.** Map of the Afar region showing magnetic isochrons (modified from Fournier et al., 2010; Bridges et
576 al., 2012; Schettino et al., 2016), earthquake locations (from ISC catalog), Holocene onshore volcano
577 locations (from GVP catalog and Viltres et al. (2020)) and recent volcanism (modified from Keir et al., 2013).

578 **Fig. 4.** Elevation of the Ethiopian–Yemen plateau (after Sembroni et al., 2016; Faccenna et al., 2019),
579 volcanic episodes and opening rates of the rift arms (modified from Fournier et al., 2010; DeMets and
580 Merkouriev, 2016; Schettino et al., 2018). Dashed lines indicate estimations from geological observations
581 and solid lines from magnetic isochrons.

582 **Fig. 5.** Gravity data of the Afar region. (a) Vertical gravity gradient from Sandwell et al. (2014). Bouguer
583 anomaly model from ICGEM, XGM2019e (Zingerle et al., 2020).

584 **Fig. 6.** (a) Difference of Gaussians applied to topography and bathymetry showing rift margins (black lines).
585 White dashed lines indicate peaks in rift width. TGD is the Tendaho-Goba’ad Discontinuity. SSD is the
586 Shukra al Sheik discontinuity. Black dots indicate earthquake locations (ISC catalog). (b) Rift widths,
587 calculated in rift-perpendicular directions.

588 **Fig. 7.** Bathymetry (a), vertical gravity gradient (b) and Bouguer anomaly (c) in the southern Red Sea. Black
589 dots indicate earthquake locations (ISC catalog). (d) Profiles across rift axis.

590 **Fig. 8.** Bathymetry (a), vertical gravity gradient (b) and Bouguer anomaly (c) in the Western Gulf of Aden.
591 Black dots indicate earthquake locations (ISC catalog). (d) Profiles across rift axis.

592 **Fig. 9.** Topography (a), vertical gravity gradient (b) and Bouguer anomaly (c) in the northern Main Ethiopian
593 Rift. Black dots indicate earthquake locations (ISC catalog). (d) Profiles across (AA') and along (BB') the rift
594 valley.

595 **Fig. 10.** Topography (a), vertical gravity gradient (b) and Bouguer anomaly (c) in the Afar triangle. Black
596 dots indicate earthquake locations (ISC catalog). TGD is the Tendaho-Goba'ad Discontinuity. (d) Profiles
597 SW (AA') and NE (BB') to the TGD.

598 **Fig. 11.** Rift margins (solid white lines) and axial segments (long dashed black lines) in the Afar region. Black
599 dots indicate earthquake locations (ISC catalog). TGD is the Tendaho-Goba'ad Discontinuity.

600 **Fig. 12.** Tilt-angle derivative map of magnetic anomalies, projected on a shaded relief after Issachar et al.
601 (2022). Purple colures represent positive angles and green colors represent negative angles. White dashed
602 lines indicate magnetic stripes (Schettino et al., 2016).

603 **Fig. 13.** Synthesis of the progressive development of the rift intersections.

604 14. References

- 605 Abebe, T., Balestrieri, M.L., and Bigazzi, G., 2010, The Central Main Ethiopian Rift is younger than 8 Ma:
606 confirmation through apatite fission-track thermochronology:, doi:10.1111/j.1365-
607 3121.2010.00968.x.
- 608 Akram, F., Garcia, M.A., and Puig, D., 2017, Active contours driven by difference of Gaussians: Scientific
609 Reports, v. 7, p. 1–15, doi:10.1038/s41598-017-14502-w.
- 610 Anderson, D.L., 2005, Large Igneous Provinces, Delamination, and Fertile Mantle: Elements, v. 1, p. 271–
611 275, doi:10.2113/gselements.1.5.271.
- 612 Anderson, D.L., 1994, The sublithospheric mantle as the source of continental flood basalts; the case
613 against the continental lithosphere and plume head reservoirs: Earth and Planetary Science Letters,
614 v. 123, p. 269–280, doi:https://doi.org/10.1016/0012-821X(94)90273-9.
- 615 Audin, L., Quidelleur, X., Coulié, E., Courtillot, V., Gilder, S., Manighetti, I., Gillot, P.Y., Tapponnier, P., and
616 Kidane, T., 2004, Palaeomagnetism and K-Ar and 40 Ar/39 Ar ages in the Ali Sabieh area (Republic of
617 Djibouti and Ethiopia): Constraints on the mechanism of Aden ridge propagation into southeastern
618 Afar during the last 10 Myr: Geophysical Journal International, v. 158, p. 327–345,
619 doi:10.1111/j.1365-246X.2004.02286.x.
- 620 Augustin, N., van der Zwan, F.M., Devey, C.W., and Brandsdóttir, B., 2021, 13 million years of seafloor
621 spreading throughout the Red Sea Basin: Nature Communications, v. 12, p. 1–10,
622 doi:10.1038/s41467-021-22586-2.
- 623 Autin, J., Bellahsen, N., Leroy, S., Husson, L., Beslier, M.O., and d'Acremont, E., 2013, The role of structural
624 inheritance in oblique rifting: Insights from analogue models and application to the Gulf of Aden:
625 Tectonophysics, v. 607, p. 51–64, doi:10.1016/J.TECTO.2013.05.041.
- 626 Barrberi, F., and Varet, J., 1977, Volcanism of Afar: Small-scale plate tectonics implications: GSA Bulletin,
627 v. 88, p. 1251–1266, doi:10.1130/0016-7606(1977)88<1251:VOASPT>2.0.CO;2.
- 628 Bellahsen, N., Faccenna, C., Funicello, F., Daniel, J.M., and Jolivet, L., 2003, Why did Arabia separate from
629 Africa? Insights from 3-D laboratory experiments: Earth and Planetary Science Letters, v. 216, p. 365–

- 630 381, doi:10.1016/S0012-821X(03)00516-8.
- 631 Bellahsen, N., Husson, L., Autin, J., Leroy, S., and D'Acromont, E., 2013, The effect of thermal weakening
632 and buoyancy forces on rift localization: Field evidences from the Gulf of Aden oblique rifting:
633 *Tectonophysics*, v. 607, p. 80–97, doi:10.1016/j.tecto.2013.05.042.
- 634 Bellieni, G., Visentin, E.J., Zanettin, B., Piccirillo, E.M., Radicati di Brozolo, F., and Rita, F., 1981, Oligocene
635 transitional tholeiitic magmatism in Northern turkana (Kenya): Comparison with the Coeval Ethiopian
636 volcanism: *Bulletin Volcanologique*, v. 44, p. 411–427, doi:10.1007/BF02600573.
- 637 Beyene, A., and Abdelsalam, M.G., 2005, Tectonics of the Afar Depression: A review and synthesis: *Journal*
638 *of African Earth Sciences*, v. 41, p. 41–59, doi:10.1016/j.jafrearsci.2005.03.003.
- 639 Bonini, M., Corti, G., Innocenti, F., Manetti, P., Mazzarini, F., Abebe, T., and Pecsckay, Z., 2005, Evolution of
640 the Main Ethiopian Rift in the frame of Afar and Kenya rifts propagation: v. 24,
641 doi:10.1029/2004TC001680.
- 642 Bosworth, W., 2015, Geological evolution of the Red Sea: historical background, review, and synthesis, *in*
643 *In The Red Sea*, Springer, Berlin, Heidelberg, p. 45–78, doi:10.1007/978-3-662-45201-1.
- 644 Bosworth, W., Huchon, P., and McClay, K., 2005, The Red Sea and Gulf of Aden Basins: *Journal of African*
645 *Earth Sciences*, v. 43, p. 334–378, doi:10.1016/j.jafrearsci.2005.07.020.
- 646 Bosworth, W., and Stockli, D.F., 2016, Early magmatism in the greater Red Sea rift: Timing and significance:
647 *Canadian Journal of Earth Sciences*, v. 53, p. 1158–1176, doi:10.1139/cjes-2016-0019.
- 648 Bridges, D.L., Mickus, K., Gao, S.S., Abdelsalam, M.G., and Alemu, A., 2012, Magnetic stripes of a
649 transitional continental rift in Afar: *Geology*, v. 40, p. 203–206, doi:10.1130/G32697.1.
- 650 Bryan, S.E., and Ferrari, L., 2013, Large igneous provinces and silicic large igneous provinces: Progress in
651 our understanding over the last 25 years: *GSA Bulletin*, v. 125, p. 1053–1078, doi:10.1130/B30820.1.
- 652 Buiter, S.J.H., and Torsvik, T.H., 2014, A review of Wilson Cycle plate margins: A role for mantle plumes in
653 continental break-up along sutures? *Gondwana Research*, v. 26, p. 627–653,
654 doi:10.1016/J.GR.2014.02.007.
- 655 Burke, K., 1996, The African Plate: *South African Journal of Geology*, v. 99, p. 341–409, doi:10.10520/EJC-
656 942801F20.
- 657 Burke, K., and Dewey, J.F., 1973, Plume-generated triple junctions: key indicators in applying plate
658 tectonics to old rocks: *The Journal of Geology*, v. 81, p. 406–433,
659 doi:https://doi.org/10.1086/627882.
- 660 Campbell, I.H., and Griffiths, R.W., 1990, Implications of mantle plume structure for the evolution of flood
661 basalts: *Earth and Planetary Science Letters*, v. 99, p. 79–93, doi:10.1016/0012-821X(90)90072-6.
- 662 Cande, S.C., and Stegman, D.R., 2011, Indian and African plate motions driven by the push force of the
663 Réunion plume head: *Nature*, v. 475, p. 47–52, doi:10.1038/nature10174.
- 664 Carbotte, S.M., Smith, D.K., Cannat, M., and Klein, E.M., 2016, Tectonic and magmatic segmentation of the
665 Global Ocean Ridge System: A synthesis of observations, *in Geological Society Special Publication*,
666 *Geological Society of London*, v. 420, p. 249–295, doi:10.1144/SP420.5.
- 667 Chatterjee, S., Goswami, A., and Scotese, C.R., 2013, The longest voyage: Tectonic, magmatic, and
668 paleoclimatic evolution of the Indian plate during its northward flight from Gondwana to Asia:
669 *Gondwana Research*, v. 23, p. 238–267, doi:10.1016/j.gr.2012.07.001.
- 670 Chorowicz, J., 2005, The East African rift system: *Journal of African Earth Sciences*, v. 43, p. 379–410,

671 doi:10.1016/j.jafrearsci.2005.07.019.

672 Collet, B., Taud, H., Parrot, J.F., Bonavia, F., and Chorowicz, J., 2000, A new kinematic approach for the
673 Danakil block using a Digital Elevation Model representation: *Tectonophysics*, v. 316, p. 343–357,
674 doi:10.1016/S0040-1951(99)00263-2.

675 Corti, G., 2009, Continental rift evolution: From rift initiation to incipient break-up in the Main Ethiopian
676 Rift, East Africa: *Earth-Science Reviews*, v. 96, p. 1–53, doi:10.1016/j.earscirev.2009.06.005.

677 Coulié, E., Quidelleur, X., Courtillot, V., Lefèvre, J.C., and Chiesa, S., 2003, Comparative K-Ar and Ar/Ar
678 dating of Ethiopian and Yemenite Oligocene volcanism: Implications for timing and duration of the
679 Ethiopian traps: *Earth and Planetary Science Letters*, v. 206, p. 477–492, doi:10.1016/S0012-
680 821X(02)01089-0.

681 Courtillot, V., Jaupart, C., Manighetti, I., Tapponnier, P., and Besse, J., 1999, On causal links between flood
682 basalts and continental breakup: *Earth and Planetary Science Letters*, v. 166, p. 177–195,
683 doi:10.1016/S0012-821X(98)00282-9.

684 Davison, I. et al., 1994, Geological evolution of the southeastern Red Sea Rift margin, Republic of Yemen:
685 *Geological Society of America Bulletin*, v. 106, p. 1474–1493, doi:10.1130/0016-
686 7606(1994)106<1474:GEOTSR>2.3.CO;2.

687 DeMets, C., and Merkouriev, S., 2016, High-resolution estimates of Nubia-Somalia plate motion since 20
688 Ma from reconstructions of the Southwest Indian Ridge, Red Sea and Gulf of Aden: *Geophysical
689 Journal International*, v. 207, p. 317–332, doi:10.1093/gji/ggw276.

690 Doubre, C. et al., 2017, Current deformation in Central Afar and triple junction kinematics deduced from
691 GPS and InSAR measurements: *Geophysical Journal International*, v. 208, p. 936–953,
692 doi:10.1093/gji/ggw434.

693 Duclaux, G., Huismans, R.S., and May, D.A., 2020, Rotation, narrowing, and preferential reactivation of
694 brittle structures during oblique rifting: *Earth and Planetary Science Letters*, v. 531, p. 115952,
695 doi:10.1016/j.epsl.2019.115952.

696 Dyer, R., 1988, Using joint interactions to estimate paleostress ratios: *Journal of Structural Geology*, v. 10,
697 p. 685–699, doi:10.1016/0191-8141(88)90076-4.

698 Ebinger, C.J., Keir, D., Bastow, I.D., Whaler, K., Hammond, J.O.S., Ayele, A., Miller, M.S., Tiberi, C., and
699 Hautot, S., 2017, Crustal Structure of Active Deformation Zones in Africa: Implications for Global
700 Crustal Processes: *Tectonics*, v. 36, p. 3298–3332, doi:https://doi.org/10.1002/2017TC004526.

701 Ernst, R.E., 2014, *Large igneous provinces*: Cambridge University Press.

702 Eyles, J.H.W., Illsley-Kemp, F., Keir, D., Ruch, J., and Jónsson, S., 2018, Seismicity Associated With the
703 Formation of a New Island in the Southern Red Sea: *Frontiers in Earth Science*, v. 6, p. 1–10,
704 doi:10.3389/feart.2018.00141.

705 Faccenna, C., Becker, T.W., Jolivet, L., and Keskin, M., 2013, Mantle convection in the Middle East:
706 Reconciling Afar upwelling, Arabia indentation and Aegean trench rollback: *Earth and Planetary
707 Science Letters*, v. 375, p. 254–269, doi:10.1016/J.EPSL.2013.05.043.

708 Faccenna, C., Glišović, P., Forte, A., Becker, T.W., Garzanti, E., Sembroni, A., and Gvirtzman, Z., 2019, Role
709 of dynamic topography in sustaining the Nile River over 30 million years: *Nature Geoscience*, v. 12,
710 p. 1012–1017, doi:10.1038/s41561-019-0472-x.

711 Forsyth, D., and Uyeda, S., 1975, On the relative importance of the driving forces of plate motion:
712 *Geophysical Journal International*, v. 43, p. 163–200.

713 Fournier, M. et al., 2010, Arabia-Somalia plate kinematics, evolution of the Aden-OwenCarlsberg triple
714 junction, and opening of the Gulf of Aden: *Journal of Geophysical Research: Solid Earth*, v. 115, p. 1–
715 24, doi:10.1029/2008JB006257.

716 François, T., Koptev, A., Cloetingh, S., Burov, E., and Gerya, T., 2018, Plume-lithosphere interactions in
717 rifted margin tectonic settings: Inferences from thermo-mechanical modelling: *Tectonophysics*, v.
718 746, p. 138–154, doi:10.1016/j.tecto.2017.11.027.

719 Frizon De Lamotte, D., Fourdan, B., Leleu, S., Leparmentier, F., and De Clarens, P., 2015, Style of rifting and
720 the stages of Pangea breakup: *Tectonics*, v. 34, p. 1009–1029, doi:10.1002/2014TC003760.

721 Fromm, T., Planert, L., Jokat, W., Ryberg, T., Behrmann, J.H., Weber, M.H., and Haberland, C., 2015, South
722 Atlantic opening: A plume-induced breakup? *Geology*, v. 43, p. 931–934, doi:10.1130/G36936.1.

723 Garfunkel, Z., 1989, Tectonic setting of phanerozoic magmatism in Israel: *Israel journal of earth-sciences*,
724 v. 38, p. 51–74.

725 Garfunkel, Z., and Beyth, M., 2006, Constraints on the structural development of Afar imposed by the
726 kinematics of the major surrounding plates: *Geological Society Special Publication*, v. 259, p. 23–42,
727 doi:10.1144/GSL.SP.2006.259.01.04.

728 Gass, I.G., Mallick, D.I.J., and Cos, K.G., 1973, Volcanic islands of the Red Sea: *Journal of the Geological*
729 *Society*, v. 129, p. 275–309, doi:10.1144/gsjgs.129.3.0275.

730 GEBCO Compilation Group, 2021, The GEBCO_2019 Grid: a continuous terrain model of the global oceans
731 and land:, doi:10.5285/c6612cbe-50b3-0cff-e053-6c86abc09f8f.

732 Geoffroy, L., 2005, Volcanic passive margins: *Comptes Rendus Geoscience*, v. 337, p. 1395–1408,
733 doi:10.1016/J.CRTE.2005.10.006.

734 George, R., Rogers, N., and Kelley, S., 1998, Earliest magmatism in Ethiopia: Evidence for two mantle
735 plumes in one flood basalt province: *Geology*, v. 26, p. 923–926, doi:10.1130/0091-
736 7613(1998)026<0923:EMIEEF>2.3.CO;2.

737 Giannerini, G., Campredon, R., Feraud, G., and Abou Zakhem, B., 1988, Deformations intraplaques et
738 volcanisme associe; exemple de la bordure NW de la plaque Arabique au Cenozoique: *Bulletin de la*
739 *Société Géologique de France*, v. IV, p. 937–947, doi:10.2113/gssgfbull.IV.6.937.

740 Gillard, M., Leroy, S., Cannat, M., and Sloan, H., 2021, Margin-to-Margin Seafloor Spreading in the Eastern
741 Gulf of Aden: A 16 Ma-Long History of Deformation and Magmatism from Seismic Reflection, Gravity
742 and Magnetic Data: *Frontiers in Earth Science*, v. 9, p. 628, doi:10.3389/feart.2021.707721.

743 Gvirtzman, Z., Faccenna, C., and Becker, T.W., 2016, Isostasy, flexure, and dynamic topography:
744 *Tectonophysics*, v. 683, p. 255–271, doi:10.1016/j.tecto.2016.05.041.

745 Hill, R.I., 1991, Starting plumes and continental break-up: *Earth and Planetary Science Letters*, v. 104, p.
746 398–416, doi:10.1016/0012-821X(91)90218-7.

747 van Hinsbergen, D.J.J. et al., 2021, A record of plume-induced plate rotation triggering subduction
748 initiation: *Nature Geoscience*, v. 14, p. 626–630, doi:10.1038/s41561-021-00780-7.

749 van Hinsbergen, D.J.J., Steinberger, B., Doubrovine, P. V., and Gassmöller, R., 2011, Acceleration and
750 deceleration of India-Asia convergence since the Cretaceous: Roles of mantle plumes and continental
751 collision: *Journal of Geophysical Research: Solid Earth*, v. 116, p. 6101, doi:10.1029/2010JB008051.

752 Hofstetter, R., and Beyth, M., 2003, The afar depression: Interpretation of the 1960-2000 earthquakes:
753 *Geophysical Journal International*, v. 155, p. 715–732, doi:10.1046/j.1365-246X.2003.02080.x.

- 754 Hughes, G.W., Varol, O., and Beydoun, Z.R., 1991, Evidence for Middle Oligocene rifting of the Gulf of Aden
755 and for Late Oligocene rifting of the southern Red Sea: *Marine and Petroleum Geology*, v. 8, p. 354–
756 358, doi:10.1016/0264-8172(91)90088-I.
- 757 Huismans, R.S., Podladchikov, Y.Y., and Cloetingh, S., 2001, Transition from passive to active rifting:
758 Relative importance of asthenospheric doming and passive extension of the lithosphere: *Journal of*
759 *Geophysical Research: Solid Earth*, v. 106, p. 11271–11291, doi:10.1029/2000JB900424.
- 760 Ilani, S., Harlavan, Y., Tarawneh, K., Rabba, I., Weinberger, R., Ibrahim, K., Peltz, S., and Steinitz, G., 2001,
761 New K-Ar ages of basalts from the Harrat Ash Shaam volcanic field in Jordan: Implications for the
762 span and duration of the upper-mantle upwelling beneath the western Arabian plate: *Geology*, v. 29,
763 p. 171–174, doi:10.1130/0091-7613(2001)029<0171:NKAAOB>2.0.CO;2.
- 764 Ince, E.S., Barthelmes, F., Reißland, S., Elger, K., Förste, C., Flechtner, F., and Schuh, H., 2019, ICGEM – 15
765 years of successful collection and distribution of global gravitational models, associated services, and
766 future plans: *Earth System Science Data*, v. 11, p. 647–674, doi:10.5194/essd-11-647-2019.
- 767 Issachar, R., Ebbing, J., and Dilixiati, Y., 2022, New magnetic anomaly map for the Red Sea reveals
768 transtensional structures associated with rotational rifting: *Scientific Reports*, v. 12, p. 1–13,
769 doi:10.1038/s41598-022-09770-0.
- 770 Ivanov, A. V., Demonterova, E.I., He, H., Perepelov, A.B., Travin, A. V., and Lebedev, V.A., 2015, Volcanism
771 in the Baikal rift: 40years of active-versus-passive model discussion: *Earth-Science Reviews*, v. 148,
772 p. 18–43, doi:10.1016/j.earscirev.2015.05.011.
- 773 Joffe, S., and Garfunkel, Z., 1987, Plate kinematics of the Red Sea – a re-evaluation: *Tectonophysics*, v. 141,
774 p. 5–22.
- 775 Jolivet, L., and Faccenna, C., 2000, Mediterranean extension and the Africa-Eurasia collision: *Tectonics*, v.
776 19, p. 1095–1106, doi:10.1029/2000TC900018.
- 777 Keen, C.E., 1985, The dynamics of rifting: deformation of the lithosphere by active and passive driving
778 forces: *Geophys. J. R. astr. Soc.*, v. 80, p. 95–120,
779 <https://academic.oup.com/gji/article/80/1/95/610547> (accessed August 2021).
- 780 Keir, D., Bastow, I.D., Pagli, C., and Chambers, E.L., 2013, The development of extension and magmatism
781 in the Red Sea rift of Afar: *Tectonophysics*, v. 607, p. 98–114, doi:10.1016/j.tecto.2012.10.015.
- 782 Keir, D., Pagli, C., Bastow, I.D., and Ayele, A., 2011, The magma-assisted removal of Arabia in Afar: Evidence
783 from dike injection in the Ethiopian rift captured using InSAR and seismicity: *Tectonics*, v. 30,
784 doi:<https://doi.org/10.1029/2010TC002785>.
- 785 Keranen, K., and Klemperer, S.L., 2008, Discontinuous and diachronous evolution of the Main Ethiopian
786 Rift : Implications for development of continental rifts: *Earth and Planetary Science Letters*, v. 265, p.
787 96–111, doi:10.1016/j.epsl.2007.09.038.
- 788 Kidane, T., 2016, Strong clockwise block rotation of the Ali-Sabieh/Aïsha Block: Evidence for opening of the
789 Afar Depression by a “saloon-door” mechanism, *in* Geological Society Special Publication, Geological
790 Society of London, v. 420, p. 209–219, doi:10.1144/SP420.10.
- 791 Koppers, A.A.P., Becker, T.W., Jackson, M.G., Konrad, K., Müller, R.D., Romanowicz, B., Steinberger, B., and
792 Whittaker, J.M., 2021, Mantle plumes and their role in Earth processes: *Nature Reviews Earth &*
793 *Environment*, v. 2, p. 382–401, doi:10.1038/s43017-021-00168-6.
- 794 Koptev, A., Gerya, T., Calais, E., Leroy, S., and Burov, E., 2018, Afar triple junction triggered by plume-
795 assisted bi-directional continental break-up: *Scientific Reports*, v. 8, p. 1–7, doi:10.1038/s41598-018-

796 33117-3.

797 Leroy, S. et al., 2013, From rifting to oceanic spreading in the Gulf of Aden: A synthesis: *Frontiers in Earth*
798 *Sciences*, v. 5, p. 385–427, doi:10.1007/978-3-642-30609-9_20.

799 Lithgow-Bertelloni, C., and Silver, P.G., 1998, Dynamic topography, plate driving forces and the African
800 superswell: *Nature*, v. 395, p. 269–272, doi:10.1038/26212.

801 Macdonald, K., Sempere, J.C., and Fox, P.J., 1984, East Pacific Rise from Siqueiros to Orozco fracture zones:
802 along- strike continuity of axial neovolcanic zone and structure and evolution of overlapping
803 spreading centers.: *Journal of Geophysical Research*, v. 89, p. 6049–6069,
804 doi:10.1029/JB089iB07p06049.

805 Maestrelli, D., Brune, S., Corti, G., Keir, D., Muluneh, A.A., and Sani, F., 2022, Analog and Numerical
806 Modeling of Rift-Rift-Rift Triple Junctions: *Tectonics*, v. 41, p. e2022TC007491,
807 doi:https://doi.org/10.1029/2022TC007491.

808 Manighetti, I., Tapponnier, P., Courtillot, V., Gallet, Y., Jacques, E., and Gillot, P.Y., 2001, Strain transfer
809 between disconnected, propagating rifts in Afar: *Journal of Geophysical Research: Solid Earth*, v. 106,
810 p. 13613–13665, doi:10.1029/2000jb900454.

811 Mattash, M.A., Pinarelli, L., Vaselli, O., Minissale, A., Al-Kadasi, M., Shawki, M.N., and Tassi, F., 2013,
812 Continental Flood Basalts and Rifting: Geochemistry of Cenozoic Yemen Volcanic Province:
813 *International Journal of Geosciences*, v. 04, p. 1459–1466, doi:10.4236/ijg.2013.410143.

814 McConnell, R., and Baker, B., 1970, The Structural Pattern of the Afro-Arabian Rift System in Relation to
815 Plate Tectonics: Discussion: *Philosophical Transactions of the Royal Society of London Series A*, v.
816 267, p. 390–391, https://www.jstor.org/stable/73628?seq=3#metadata_info_tab_contents
817 (accessed August 2021).

818 McDougall, I. an, and Brown, F.H., 2009, Timing of volcanism and evolution of the northern Kenya Rift:
819 *Geological Magazine*, v. 146, p. 34–47, doi:DOI: 10.1017/S0016756808005347.

820 Meshesha, D., and Shinjo, R., 2008, Rethinking geochemical feature of the Afar and Kenya mantle plumes
821 and geodynamics implications: *Journal of Geophysical Research: Solid Earth*, v. 113, p. 9209,
822 doi:10.1029/2007JB005549.

823 Mitchell, N.C., and Bosworth, (in press), W. The tectonic stability of Arabia, *in* Rasul, N.M.A. and Stewart,
824 I.C.F. eds., *The tectonic stability of Arabia, in Rifting and sediments in the Red Sea and Arabian Gulf*
825 *regions*, Taylor & Francis.

826 Mitchell, N.C., and Sofianos, S.S., 2018, Origin of submarine channel north of hanish sill, red sea, *in*
827 *Geological Setting, Palaeoenvironment and Archaeology of the Red Sea*, Springer International
828 Publishing, p. 259–273, doi:10.1007/978-3-319-99408-6_12.

829 Mitra, S., Mitra, K., Gupta, S., Bhattacharya, S., Chauhan, P., and Jain, N., 2017, Alteration and submergence
830 of basalts in Kachchh, Gujarat, India: implications for the role of the Deccan Traps in the India–
831 Seychelles break-up: *Geological Society, London, Special Publications*, v. 445, p. 47–67,
832 doi:10.1144/SP445.9.

833 Morag, N., Haviv, I., Eyal, M., Kohn, B.P., and Feinstein, S., 2019, Early flank uplift along the Suez Rift:
834 Implications for the role of mantle plumes and the onset of the Dead Sea Transform: *Earth and*
835 *Planetary Science Letters*, v. 516, p. 56–65, doi:10.1016/j.epsl.2019.03.002.

836 Moretti, I., and Froidevaux, C., 1986, Thermomechanical models of active rifting: *Tectonics*, v. 5, p. 501–
837 511, doi:10.1029/TC005I004P00501.

- 838 Morgan, W.J., 1971, Convection plumes in the lower mantle: *Nature*, v. 230, p. 42–43,
839 doi:10.1038/230042a0.
- 840 Okwokwo, O.I., Mitchell, N.C., Shi, W., Stewart, I.C.F., and Izzeldin, A.Y., 2022, How have thick evaporites
841 affected early seafloor spreading magnetic anomalies in the Central Red Sea? *Geophysical Journal*
842 *International*, v. 229, p. 1550–1566, doi:10.1093/gji/ggac012.
- 843 Pagli, C., Wang, H., Wright, T.J., Calais, E., and Lewi, E., 2014, Current plate boundary deformation of the
844 Afar rift from a 3-D velocity field inversion of InSAR and GPS: *Journal of Geophysical Research: Solid*
845 *Earth*, v. 119, p. 8562–8575, doi:https://doi.org/10.1002/2014JB011391.
- 846 Pagli, C., Yun, S.-H., Ebinger, C., Keir, D., and Wang, H., 2018, Strike-slip tectonics during rift linkage:
847 *Geology*, v. 47, p. 31–34, doi:10.1130/G45345.1.
- 848 Peate, I.U., Baker, J.A., Al-Kadasi, M., Al-Subbary, A., Knight, K.B., Riisager, P., Thirlwall, M.F., Peate, D.W.,
849 Renne, P.R., and Menzies, M.A., 2005, Volcanic stratigraphy of large-volume silicic pyroclastic
850 eruptions during Oligocene Afro-Arabian flood volcanism in Yemen: *Bulletin of Volcanology*, v. 68, p.
851 135–156, doi:10.1007/s00445-005-0428-4.
- 852 Le Pichon, X., and Gaulier, J.-M., 1988, The rotation of Arabia and the Levant fault system: *Tectonophysics*,
853 v. 153, p. 271–294, doi:10.1016/0040-1951(88)90020-0.
- 854 Plaziat, J.-C., Baltzer, F., Choukri, A., Conchon, O., Freydet, P., Orszag-Sperber, F., Raguideau, A., and Reyss,
855 J.-L., 1998, Quaternary marine and continental sedimentation in the northern Red Sea and Gulf of
856 Suez (Egyptian coast): influences of rift tectonics, climatic changes and sea-level fluctuations, *in*
857 *Sedimentation and Tectonics in Rift Basins Red Sea:- Gulf of Aden*, Springer Netherlands, p. 537–573,
858 doi:10.1007/978-94-011-4930-3_29.
- 859 Prave, A.R., Bates, C.R., Donaldson, C.H., Toland, H., Condon, D.J., Mark, D., and Raub, T.D., 2016, Geology
860 and geochronology of the Tana Basin, Ethiopia: LIP volcanism, Super eruptions and Eocene-Oligocene
861 environmental change: *Earth and Planetary Science Letters*, v. 443, p. 1–8,
862 doi:10.1016/j.epsl.2016.03.009.
- 863 Pusok, A.E., and Stegman, D.R., 2020, The convergence history of India-Eurasia records multiple
864 subduction dynamics processes: *Science Advances*, v. 6,
865 doi:10.1126/SCIADV.AAZ8681/SUPPL_FILE/AAZ8681_SM.PDF.
- 866 Qaysi, S., Liu, K.H., and Gao, S.S., 2018, A Database of Shear-Wave Splitting Measurements for the Arabian
867 Plate: *Seismological Research Letters*, v. 89, p. 2294–2298, doi:10.1785/0220180144.
- 868 Reilinger, R. et al., 2006, GPS constraints on continental deformation in the Africa-Arabia-Eurasia
869 continental collision zone and implications for the dynamics of plate interactions: *Journal of*
870 *Geophysical Research-Solid Earth*, v. 111.
- 871 Reilinger, R., and McClusky, S., 2011, Nubia-Arabia-Eurasia plate motions and the dynamics of
872 Mediterranean and Middle East tectonics: *Geophysical Journal International*, v. 186, p. 971–979,
873 doi:10.1111/j.1365-246X.2011.05133.x.
- 874 Richards, M.A., Duncan, R.A., and Courtillot, V.E., 1989, Flood basalts and hot-spot tracks: Plume heads
875 and tails: *Science*, v. 246, p. 103–107, doi:10.1126/science.246.4926.103.
- 876 Rime, V., Foubert, A., Ruch, J., and Kidane, T., 2023, Tectonostratigraphic evolution and significance of the
877 Afar Depression: *Earth-Science Reviews*, v. 244, p. 104519,
878 doi:https://doi.org/10.1016/j.earscirev.2023.104519.
- 879 Roger, J., Platel, J.P., Cavelier, C., and Bourdillon-de-Grissac, C., 1989, Données nouvelles sur la

- 880 stratigraphie et l'histoire géologique du Dhofar (Sultanat d'Oman): Bulletin de la Société géologique
881 de France, v. 2, p. 256–277, In France, abstract in English.
- 882 Rooney, T.O., 2017, The Cenozoic magmatism of East-Africa: Part I — Flood basalts and pulsed magmatism:
883 Lithos, v. 286–287, p. 264–301, doi:10.1016/j.lithos.2017.05.014.
- 884 Sandwell, D.T., Müller, R.D., Smith, W.H.F., Garcia, E., and Francis, R., 2014, New global marine gravity
885 model from CryoSat-2 and Jason-1 reveals buried tectonic structure: Science, v. 346, p. 65–67,
886 doi:10.1126/SCIENCE.1258213.
- 887 Schettino, A., Macchiavelli, C., Pierantoni, P.P., Zanoni, D., and Rasul, N., 2016, Recent kinematics of the
888 tectonic plates surrounding the red sea and gulf of aden: Geophysical Journal International, v. 207,
889 p. 457–480, doi:10.1093/gji/ggw280.
- 890 Schettino, A., Macchiavelli, C., and Rasul, N.M.A., 2018, Plate motions around the red sea since the early
891 oligocene, in Geological Setting, Palaeoenvironment and Archaeology of the Red Sea, Springer
892 International Publishing, p. 203–220, doi:10.1007/978-3-319-99408-6_9.
- 893 Schult, A., 1974, Palaeomagnetism of tertiary volcanic rocks from the Ethiopian southern plateau and the
894 Danakil block: Journal of Geophysics, v. 40, p. 203–212,
895 <https://journal.geophysicsjournal.com/JofG/article/view/277> (accessed June 2021).
- 896 Sembroni, A., Faccenna, C., Becker, T.W., Molin, P., and Abebe, B., 2016, Long-term, deep-mantle support
897 of the Ethiopia-Yemen Plateau: Tectonics, v. 35, p. 469–488, doi:10.1002/2015TC004000.Received.
- 898 Sengör, A.M.C., and Burke, K., 1978, Relative timing of rifting and volcanism on Earth and its tectonic
899 implications: Geophysical Research Letters, v. 5, p. 419–421, doi:10.1029/GL005I006P00419.
- 900 Sobolev, S. V., Sobolev, A. V., Kuzmin, D. V., Krivolutskaya, N.A., Petrunin, A.G., Arndt, N.T., Radko, V.A.,
901 and Vasiliev, Y.R., 2011, Linking mantle plumes, large igneous provinces and environmental
902 catastrophes: Nature, v. 477, p. 312–316, doi:10.1038/nature10385.
- 903 Stamps, D.S., Flesch, L.M., Calais, E., and Ghosh, A., 2014, Current kinematics and dynamics of Africa and
904 the East African Rift System: Journal of Geophysical Research: Solid Earth, v. 119, p. 5161–5186,
905 doi:10.1002/2013JB010717.
- 906 Stockli, D.F., and Bosworth, W.B., 2018, Timing of extensional faulting along the magma-poor central and
907 northern red sea rift margin-transition from regional extension to necking along a hyperextended
908 rifted margin, in Geological Setting, Palaeoenvironment and Archaeology of the Red Sea, Springer
909 International Publishing, p. 81–111, doi:10.1007/978-3-319-99408-6_5.
- 910 Su, H., and Zhou, J., 2020, Timing of Arabia-Eurasia collision: Constraints from restoration of crustal-scale
911 cross-sections: Journal of Structural Geology, v. 135, p. 104041, doi:10.1016/j.jsg.2020.104041.
- 912 Szymanski, E., Stockli, D.F., Johnson, P.R., and Hager, C., 2016, Thermochronometric evidence for diffuse
913 extension and two-phase rifting within the Central Arabian Margin of the Red Sea Rift: Tectonics, v.
914 35, p. 2863–2895, doi:10.1002/2016TC004336.
- 915 Tazieff, H.T., Varet, J., Barberi, F., and Giglia, G., 1972, Tectonic significance of the Afar (or Danakil)
916 depression: Nature, v. 235, p. 144–147.
- 917 Tesfaye, S., Harding, D.J., and Kusky, T.M., 2003, Early continental breakup boundary and migration of the
918 Afar triple junction, Ethiopia: Bulletin of the Geological Society of America, v. 115, p. 1053–1067,
919 doi:10.1130/B25149.1.
- 920 Varet, J., 2018, Geology of Afar (East Africa): 1–249 p.

921 Varet, J., 1978, Geology of central and southern Afar (Ethiopia and Djibouti Republic): Paris, Centre
922 national de la recherche scientifique.

923 Viltres, R., Jónsson, S., Alothman, A.O., Liu, S., Leroy, S., Masson, F., Doubre, C., and Reilinger, R., 2022,
924 Present-Day Motion of the Arabian Plate: Tectonics, v. 41, p. e2021TC007013,
925 doi:<https://doi.org/10.1029/2021TC007013>.

926 Viltres, R., Jónsson, S., Ruch, J., Doubre, C., Reilinger, R., Floyd, M., and Ogubazghi, G., 2020, Kinematics
927 and deformation of the southern Red Sea region from GPS observations: Geophysical Journal
928 International, v. 221, p. 2143–2154, doi:10.1093/gji/ggaa109.

929 Watchorn, F., Nichols, G.J., and Bosence, D.W.J., 1998, Rift-related sedimentation and stratigraphy,
930 southern Yemen (Gulf of Aden), *in* Sedimentation and Tectonics in Rift Basins Red Sea:- Gulf of Aden,
931 Springer Netherlands, p. 165–189, doi:10.1007/978-94-011-4930-3_11.

932 Wescott, W.A., Wigger, S.T., Stone, D.M., and Morley, C.K., 1999, AAPG Studies in Geology# 44, Chapter 3:
933 Geology and Geophysics of the Lotikipi Plain:

934 White, R., and McKenzie, D., 1989, Magmatism at rift zones: the generation of volcanic continental margins
935 and flood basalts: Journal of Geophysical Research, v. 94, p. 7685–7729,
936 doi:10.1029/JB094iB06p07685.

937 White, R.S., and McKenzie, D., 1995, Mantle plumes and flood basalts: Journal of Geophysical Research, v.
938 100, p. 543–560, doi:10.1029/95jb01585.

939 Will, T.M., and Frimmel, H.E., 2018, Where does a continent prefer to break up? Some lessons from the
940 South Atlantic margins: Gondwana Research, v. 53, p. 9–19, doi:10.1016/j.gr.2017.04.014.

941 Wilson, J.T., 1963, A possible origin of the Hawaiian Islands: Canadian Journal of Physics, v. 41, p. 863–870,
942 doi:10.1139/P63-094.

943 Wolfenden, E., Ebinger, C., Yirgu, G., Deino, A., and Ayalew, D., 2004, Evolution of the northern Main
944 Ethiopian rift: Birth of a triple junction: Earth and Planetary Science Letters, v. 224, p. 213–228,
945 doi:10.1016/j.epsl.2004.04.022.

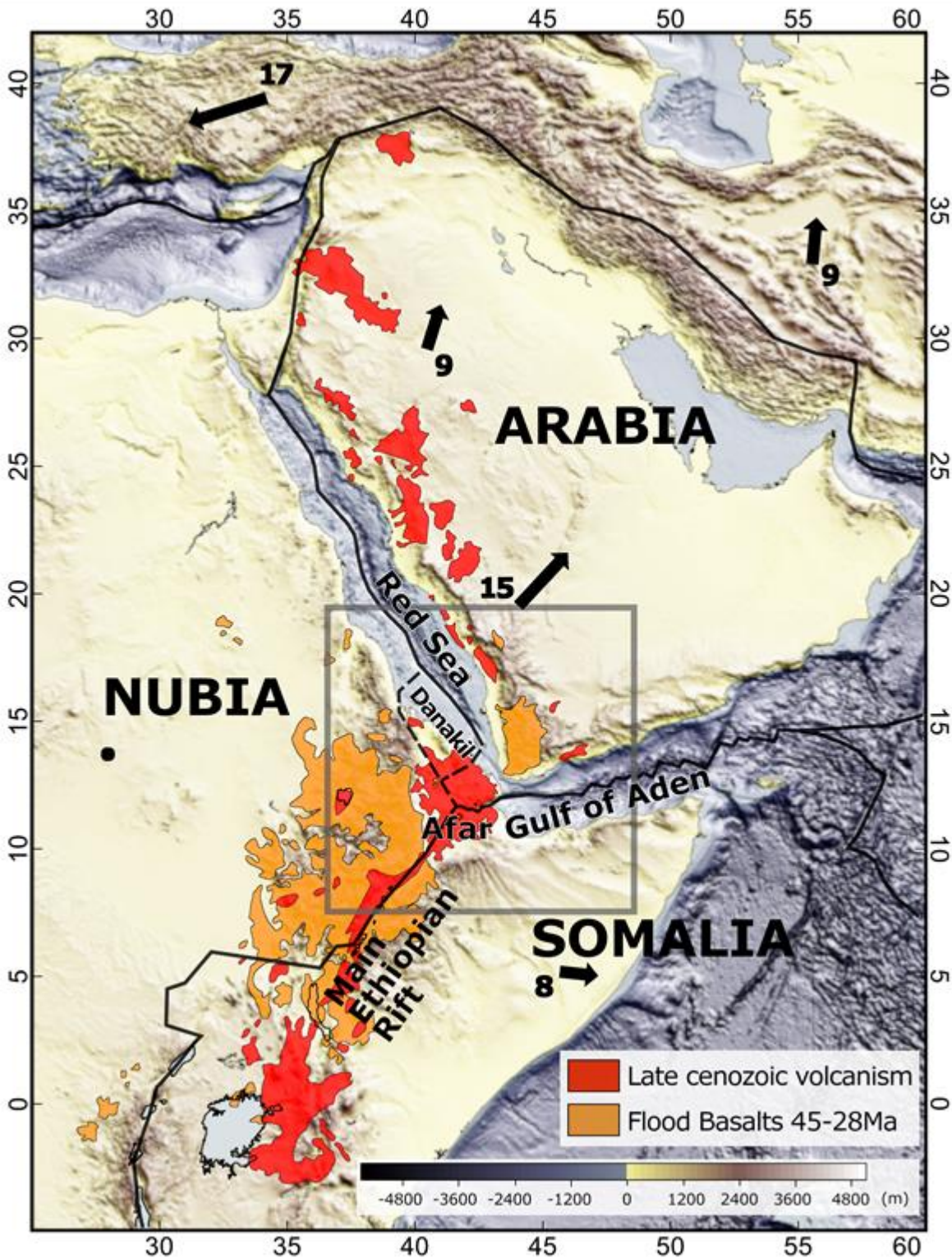
946 Zingerle, P., Pail, R., Gruber, T., and Oikonomidou, X., 2020, The combined global gravity field model
947 XGM2019e: Journal of Geodesy 2020 94:7, v. 94, p. 1–12, doi:10.1007/S00190-020-01398-0.

948 Zwaan, F., Corti, G., Keir, D., and Sani, F., 2020a, A review of tectonic models for the rifted margin of Afar:
949 Implications for continental break-up and passive margin formation: Journal of African Earth
950 Sciences, v. 164, doi:10.1016/j.jafrearsci.2019.103649.

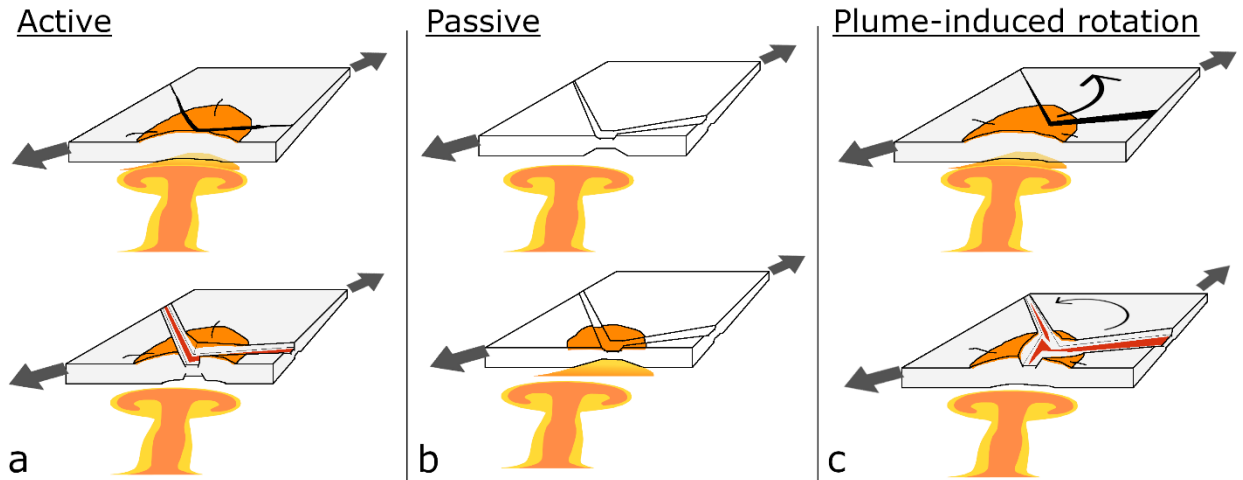
951 Zwaan, F., Corti, G., Sani, F., Keir, D., Muluneh, A.A., Illsley-Kemp, F., and Papini, M., 2020b, Structural
952 Analysis of the Western Afar Margin, East Africa: Evidence for Multiphase Rotational Rifting:
953 Tectonics, v. 39, doi:10.1029/2019TC006043.

954

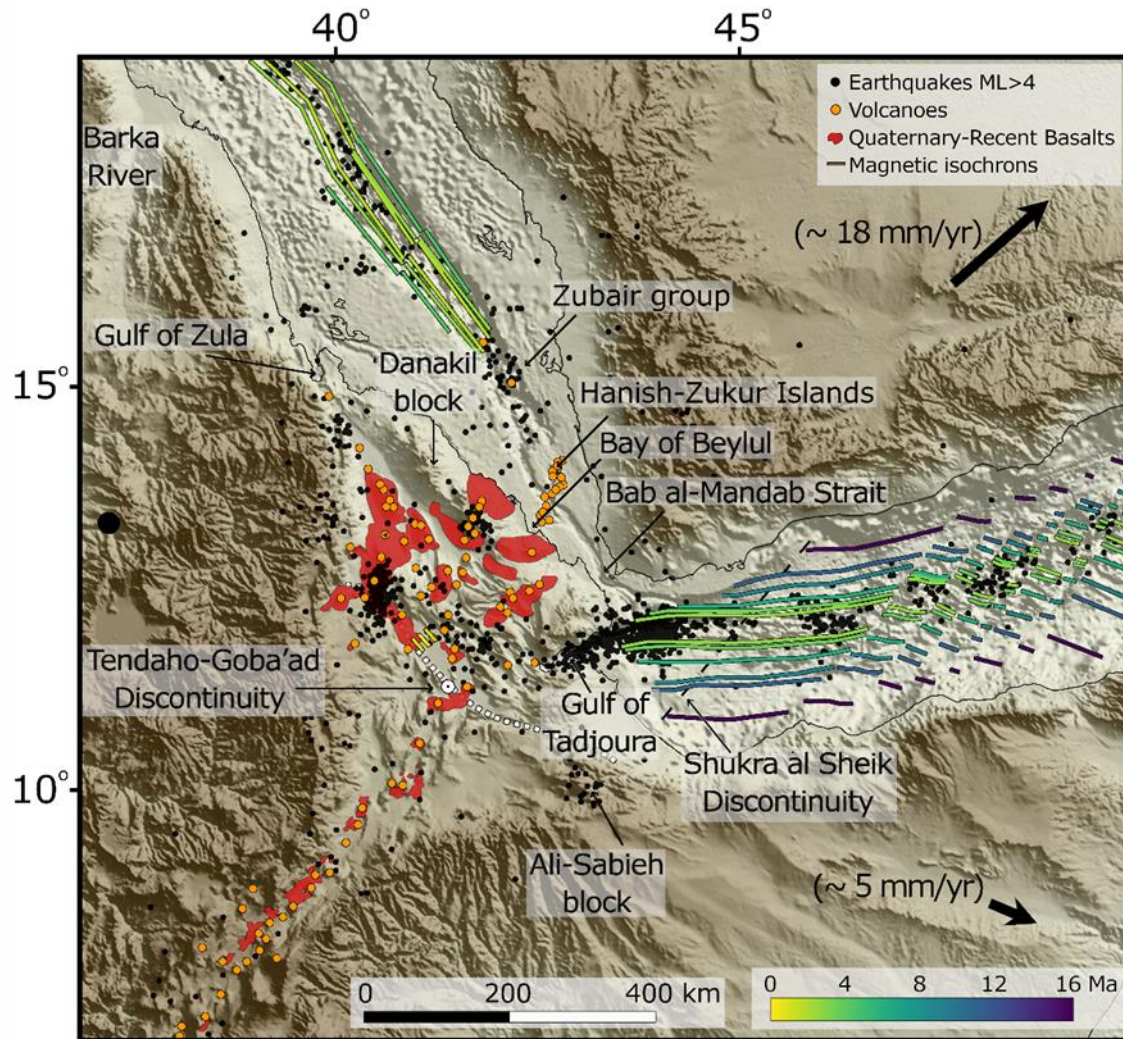
955



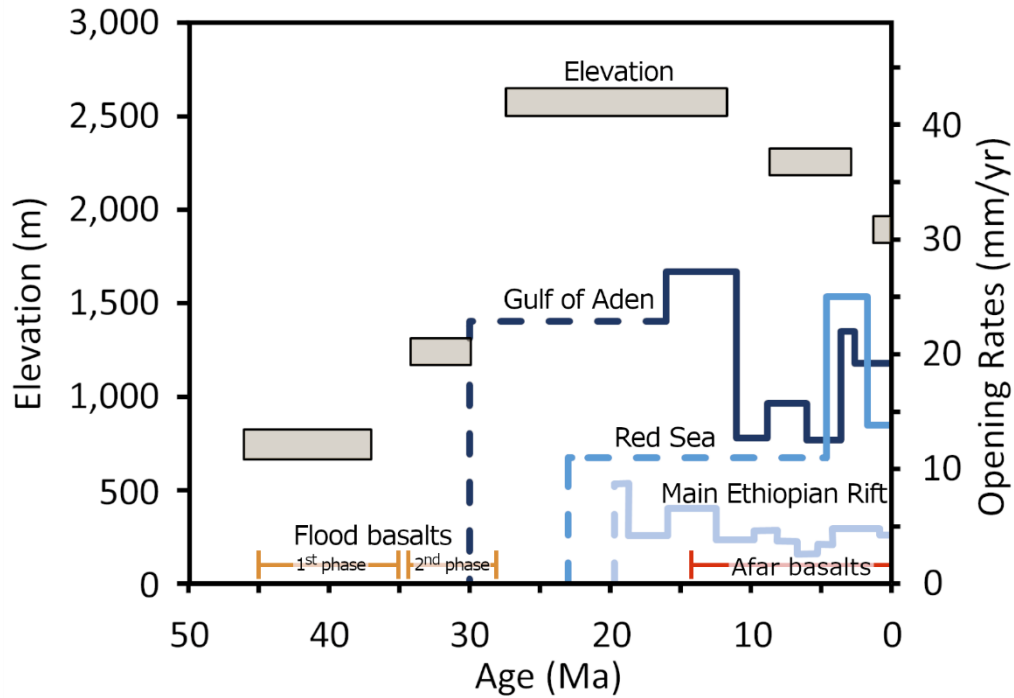
956
 957 **Figure 1.** Elevation map of the study area, showing the general plate tectonic configuration (from USGS
 958 and from Viltres et al. (2020) in the Afar region) and Cenozoic volcanics (modified from Varet, 1978;
 959 Davison et al., 1994; Beyene and Abdelsalam, 2005; Bosworth and Stockli, 2016) Black arrows indicate GPS
 960 velocities in respect to Nubia (modified from Reilinger et al., 2006).



961
 962 **Figure 2.** Schematic mechanisms for plume-rift association in the Afro-Arabian rift. (a) Active mechanism,
 963 in which rifting results from the actively rising head of the Afar plume. In this mechanism impinging and
 964 eroding the base of the lithosphere prompt uplift and decompression melting and flood basalts volcanism.
 965 These introduce internal extensional forces and ultimately lead to break-up. (b) Passive mechanism, in
 966 which rifting is initiated solely by the remote stresses, regardless of underlying Afar plume. In this
 967 mechanism the production of massive volcanism is allowed when the thinned and stretched lithosphere
 968 is underlain by the thermal anomaly in the mantle. Flood basalts volcanism is generated by passively rising
 969 decompression melting of hot asthenospheric mantle. (c) Plume-induced plate rotation, in which lateral
 970 forces, induced by the arrival of the Afar plume head, add up to the remote stresses to change the plate
 971 kinematics. In this mechanism flood basalts volcanism is actively controlled, however, rifting is triggered
 972 by the new plate kinematics.

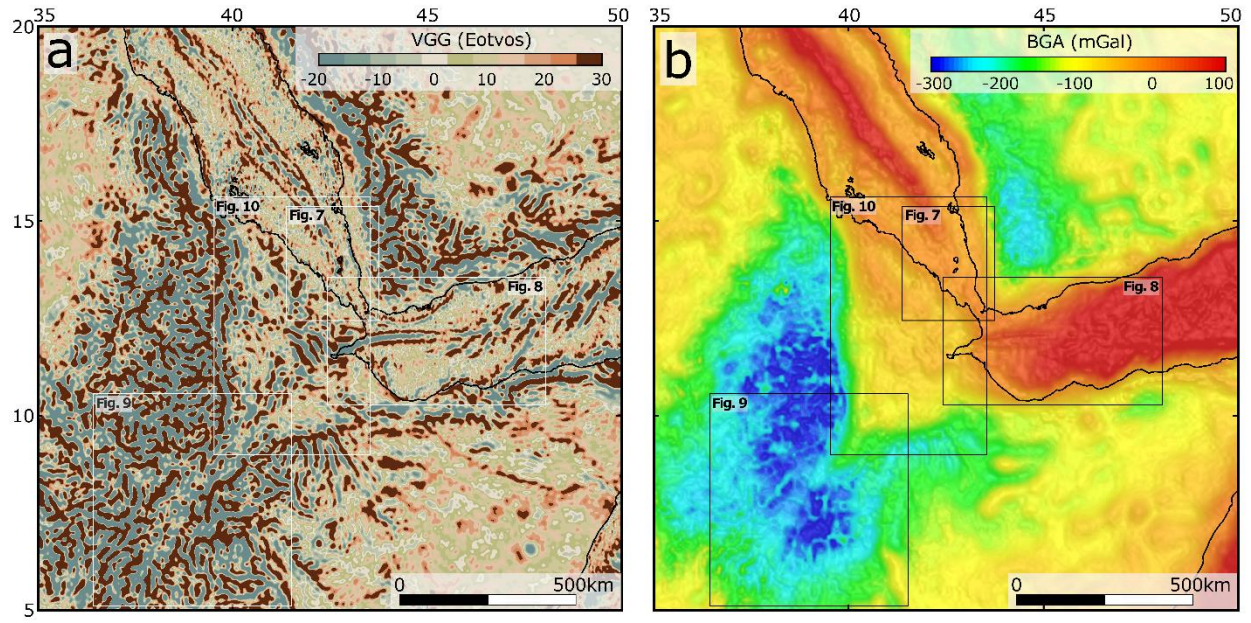


973
 974 **Figure 3.** Map of the Afar region showing magnetic isochrons (modified from Fournier et al., 2010; Bridges
 975 et al., 2012; Schettino et al., 2016), earthquake locations (from ISC catalog), Holocene onshore volcano
 976 locations (from GVP catalog and Viltres et al. (2020)) and recent volcanism (modified from Keir et al., 2013).

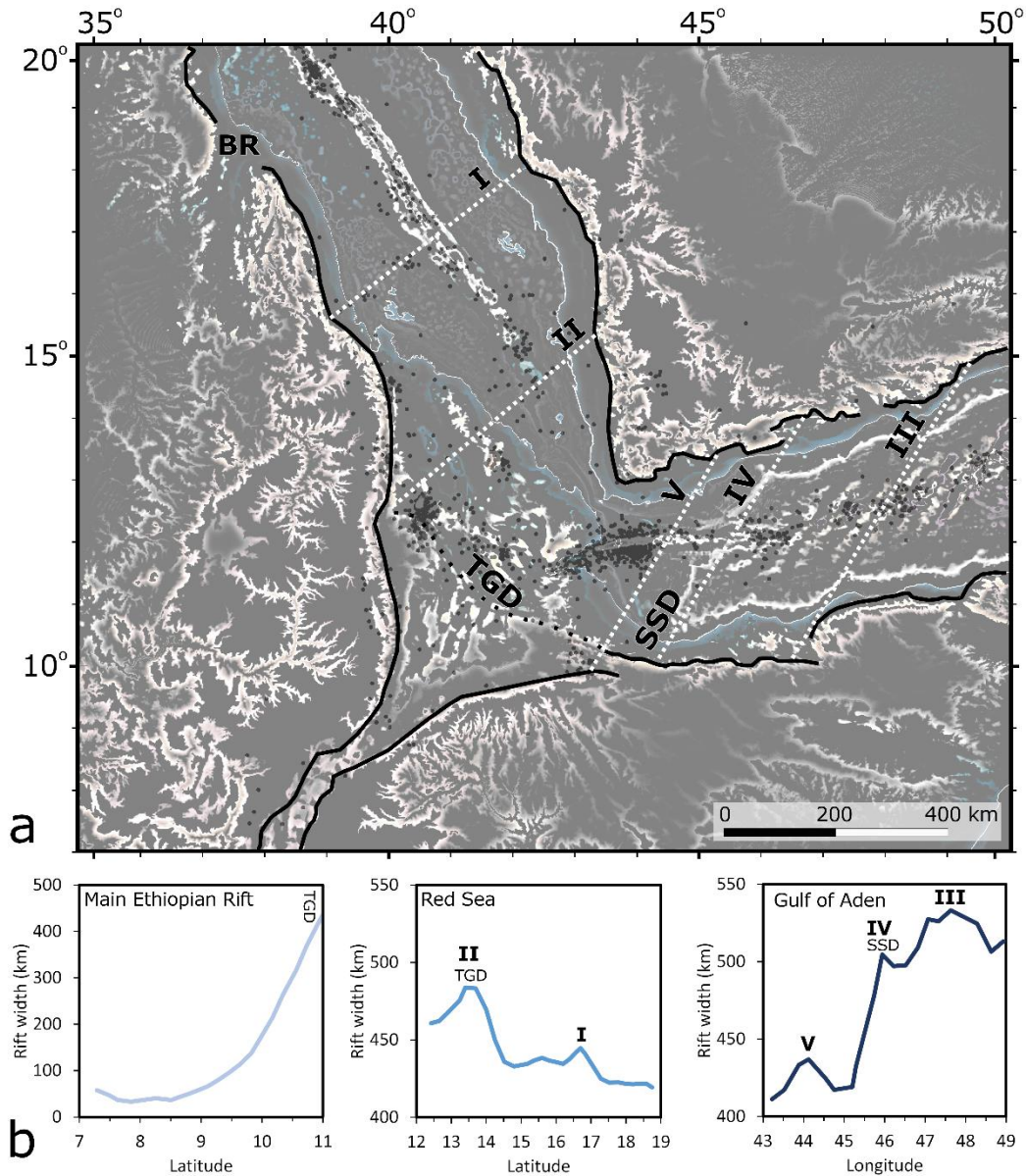


977
 978 **Figure 4.** Elevation of the Ethiopian–Yemen plateau (after Sembroni et al., 2016; Faccenna et al., 2019),
 979 volcanic episodes and opening rates of the rift arms (modified from Fournier et al., 2010; DeMets and
 980 Merkouriev, 2016; Schettino et al., 2018). Dashed lines indicate estimations from geological observations
 981 and solid lines from magnetic isochrons.

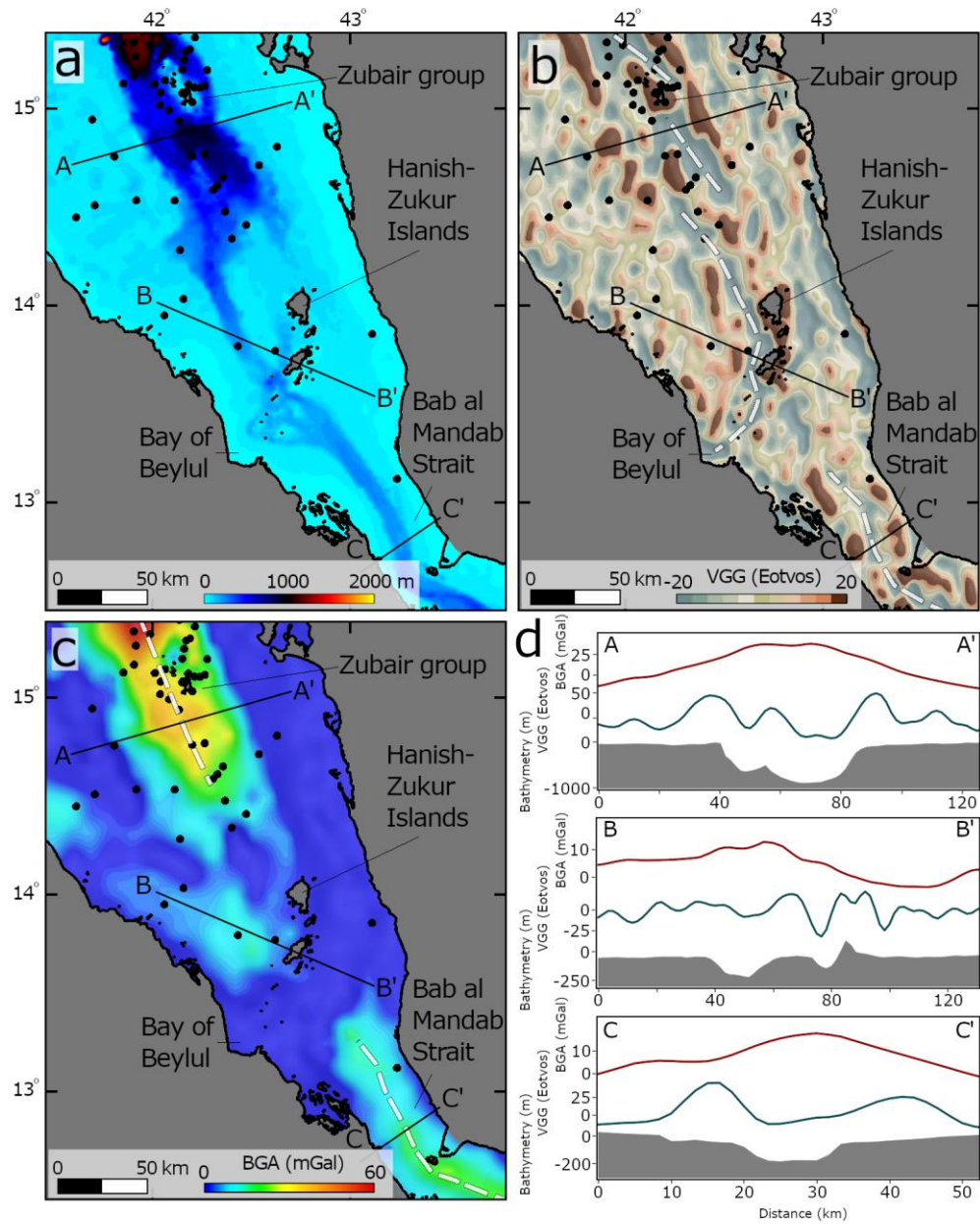
982
 983
 984
 985
 986



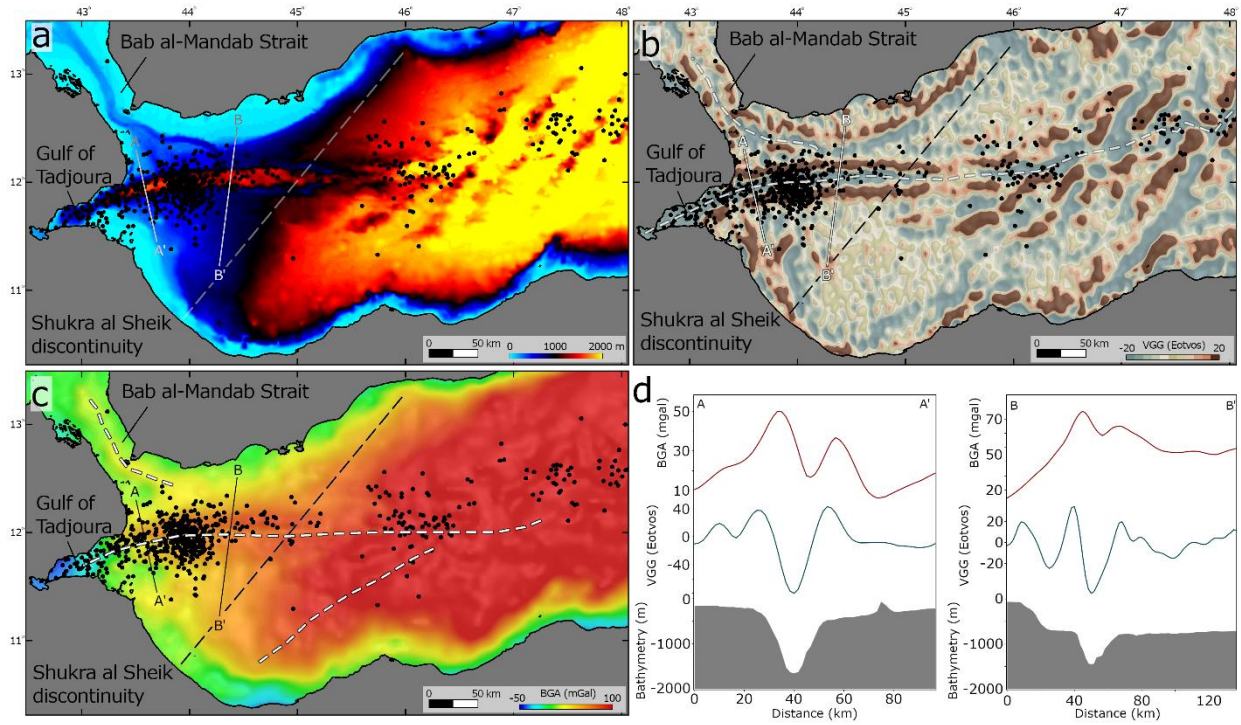
987
 988 **Figure 5.** Gravity data of the Afar region. (a) Vertical gravity gradient from Sandwell et al. (2014). (b)
 989 Bouguer anomaly model from ICGEM, XGM2019e (Zingerle et al., 2020).



990
 991 **Figure 6.** (a) Difference of Gaussians applied to topography and bathymetry showing rift margins (black
 992 lines). White dashed lines indicate peaks in rift width. TGD is the Tendaho-Goba'ad Discontinuity. SSD is
 993 the Shukra al Sheik discontinuity. Black dots indicate earthquake locations (ISC catalog). (b) Rift widths,
 994 calculated in rift-perpendicular directions.

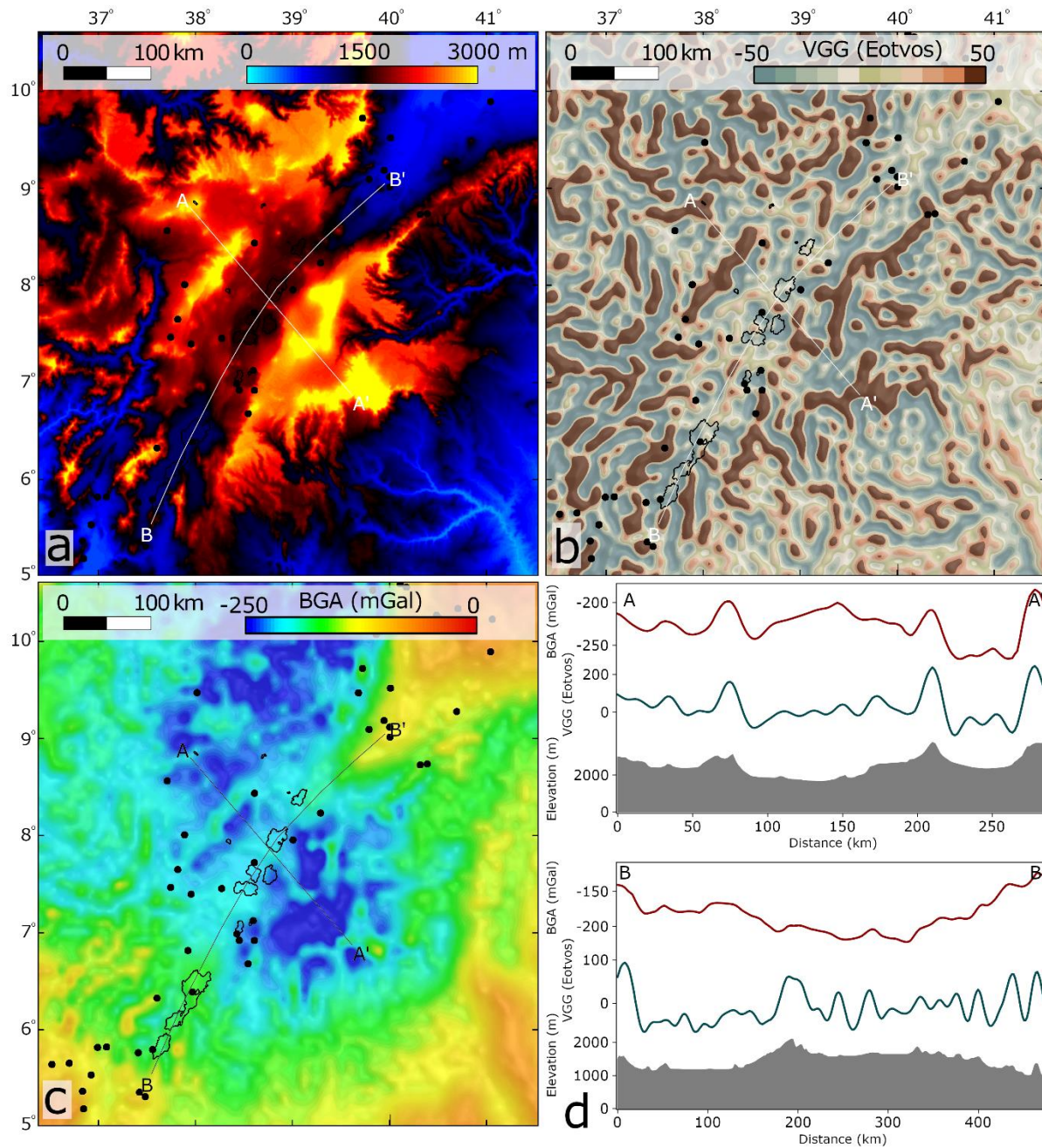


995
 996 **Figure 7.** Bathymetry (a), vertical gravity gradient (b) and Bouguer anomaly (c) in the southern Red Sea.
 997 Black dots indicate earthquake locations (ISC catalog). (d) Profiles across rift axis.



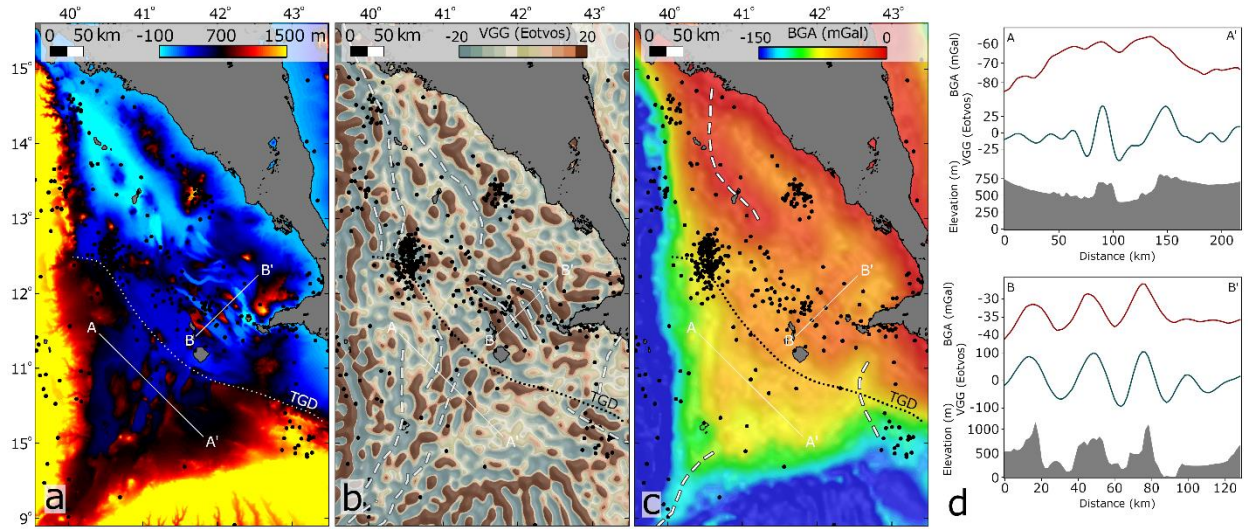
998

999 **Figure 8.** Bathymetry (a), vertical gravity gradient (b) and Bouguer anomaly (c) in the Western Gulf of Aden.
 1000 Black dots indicate earthquake locations (ISC catalog). (d) Profiles across rift axis.

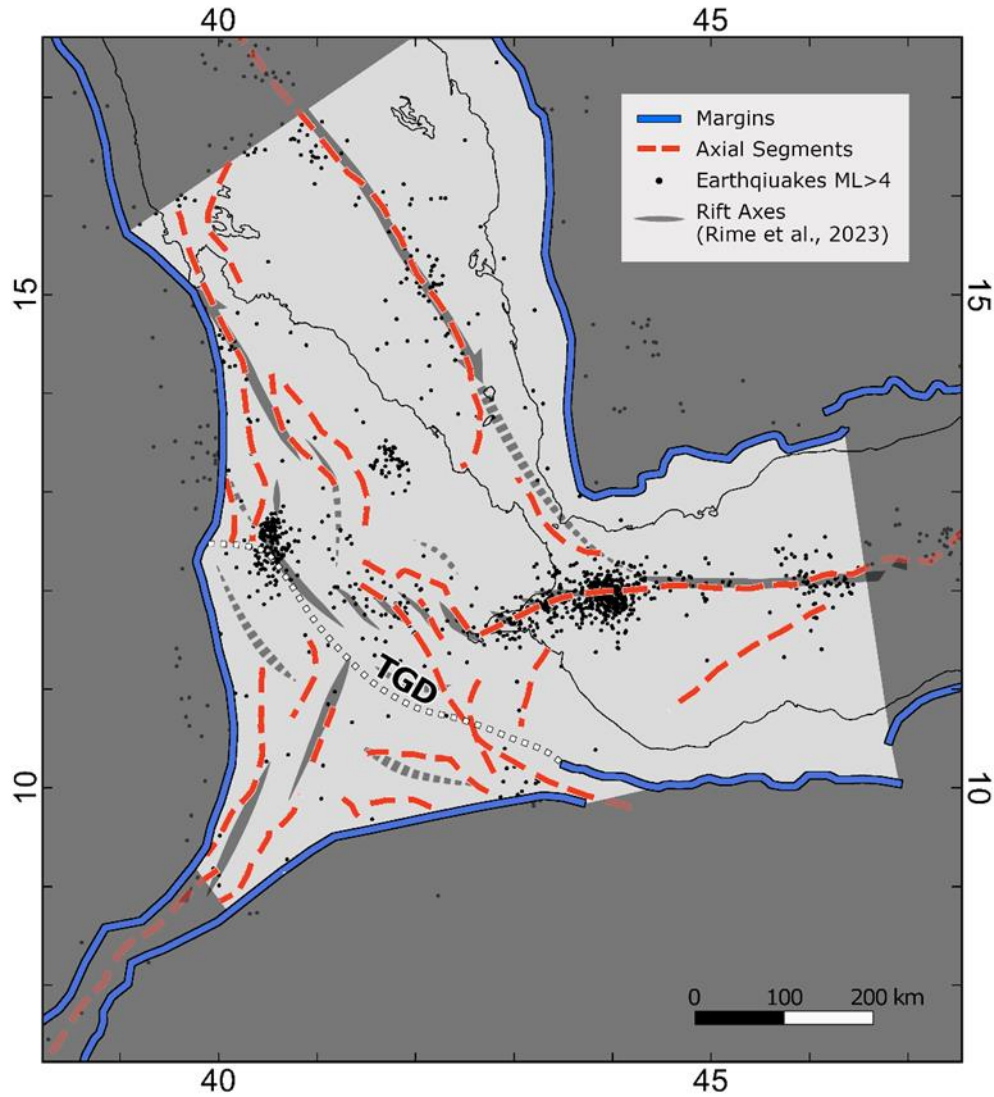


1001

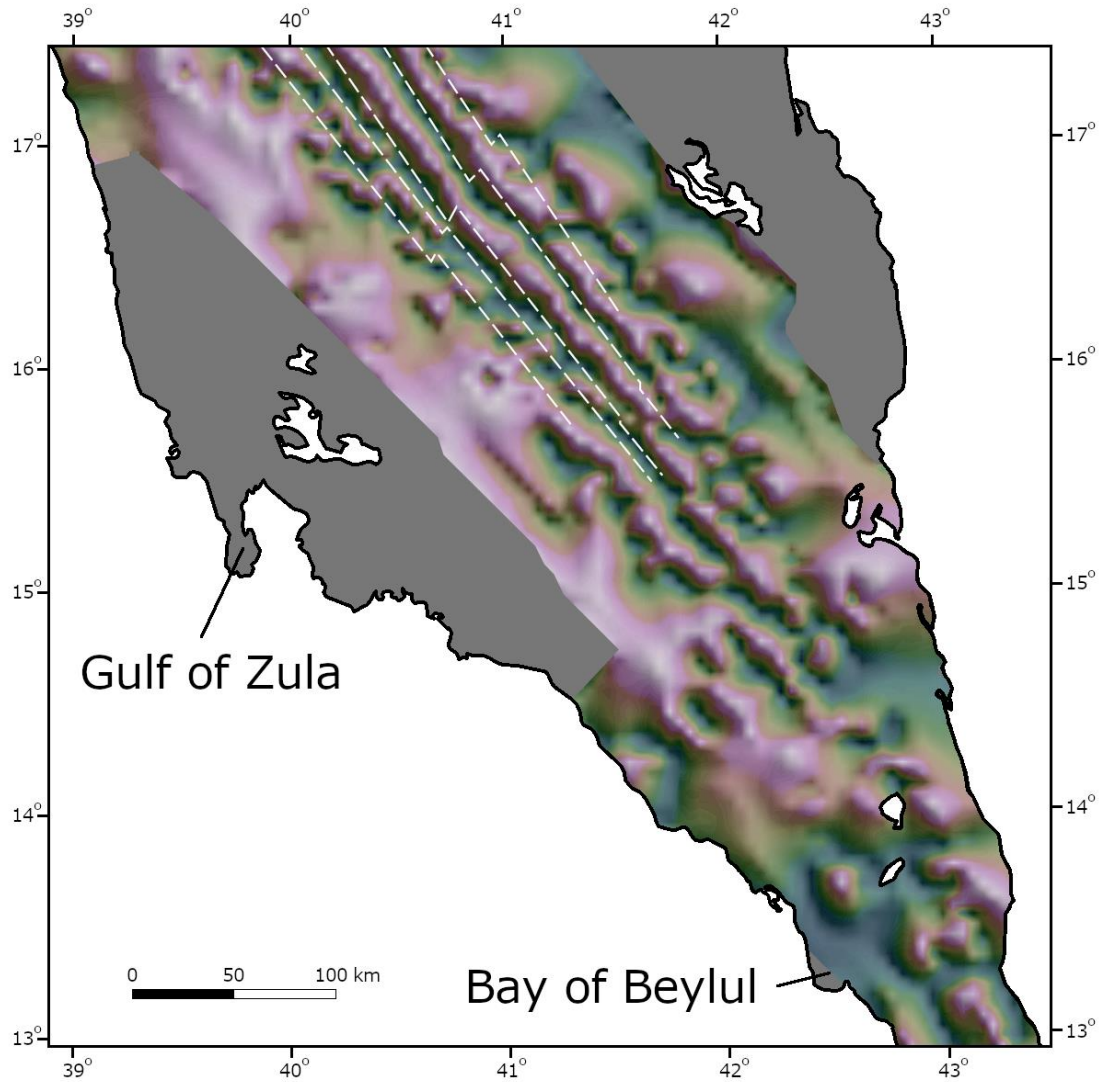
1002 **Figure 9.** Topography (a), vertical gravity gradient (b) and Bouguer anomaly (c) in the northern Main
 1003 Ethiopian Rift. Black dots indicate earthquake locations (ISC catalog). (d) Profiles across (AA') and along
 1004 (BB') the rift valley.



1005
 1006 **Figure 10.** Topography (a), vertical gravity gradient (b) and Bouguer anomaly (c) in the Afar triangle. Black
 1007 dots indicate earthquake locations (ISC catalog). TGD is the Tendaho-Goba'ad Discontinuity. (d) Profiles
 1008 SW (AA') and NE (BB') to the TGD.

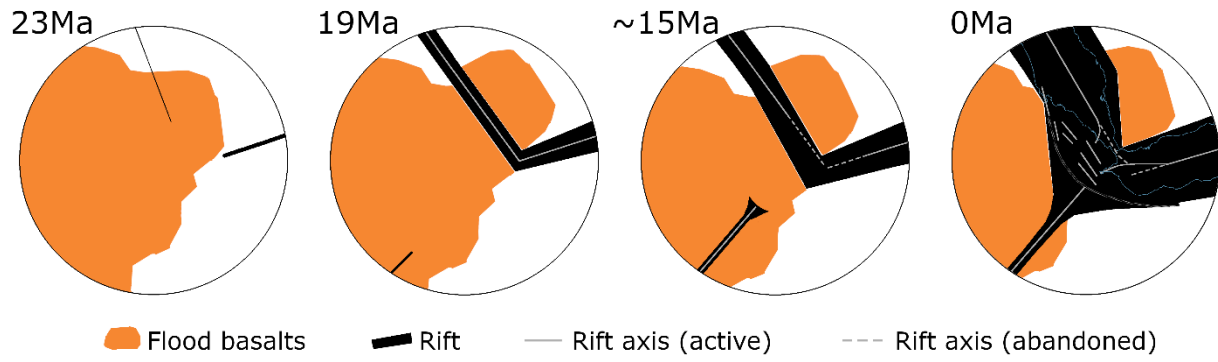


1009
 1010 **Figure 11.** Rift margins and axial segments in the Afar region. Black dots indicate earthquake locations
 1011 (ISC catalog). TGD is the Tendaho-Goba'ad Discontinuity. Rift axes based on field observations after Rime
 1012 et al. (2023).



1013
 1014 **Figure 12.** Tilt-angle derivative map of magnetic anomalies, projected on a shaded relief after Issachar et
 1015 al. (2022). Purple colors represent positive angles and green colors represent negative angles. White
 1016 dashed lines indicate magnetic stripes (Schettino et al., 2016).

1017
 1018
 1019
 1020
 1021
 1022
 1023



1024

1025

Figure 13. Synthesis of the progressive development of the rift intersections.