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

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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 relationship, 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 and separate 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 the development of 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 to 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 rifting and ultimately the break-up of Arabia from Africa.

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.

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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. Continental flood basalts, often referred to as traps, form large igneous provinces covering huge continental areas (Bryan and Ferrari, 2013; Ernst, 2014). They are associated with extensive volcanism during short time intervals, brought to the surface by deep-seated mantle plumes (Richards et al., 1989; White and McKenzie, 1995; Koppers et al., 2021). Observations indicate a close temporal and spatial occurrence between the eruption of flood basalts and continental break-up. In particular, when reconstructed back to their original plate tectonic configuration, a R-R-R triple junction is found within the flood basalts areas (Morgan, 1971; Burke and Dewey, 1973; Buiter and Torsvik, 2014). Using the geological record to examine the mutual dependency of these processes is challenging. It requires high-precision constraints regarding the temporal and spatial development of the different volcanic and tectonic features, often obscured by the long geological history.

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

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

2. Active and passive mechanisms for plume-rift association

The existence of deep mantle convection and its interaction with the Earth's crust was already pointed out by Wilson (1963), and a close occurrence to continental break-up was soon noticed by the abundance of hotspots near many rift junctions (Morgan, 1971) and flood basalts volcanism along passive margins (Richards et al., 1989). This led Morgan (1971) to speculate that deep mantle convection has a significant role in accelerating the overlying tectonic plates. Nevertheless, it was later realized that slab-pull provides the main driving force for plate motion. Furthermore, plumes are thought to have a major role in plate tectonics, triggering rifting by weakening the upper lithosphere. In their landmark paper, Burke and Dewey (1973) presented 45 case studies of rift junctions associated with hot spots. They proposed a model in which plume-associated uplift and volcanism precede and generate rifts, initiated from a triple junction within the plume region. Afar was used as a first and prime example, highlighting its importance as a young and active case study; however, they already noted its complexity (Burke and Dewey, 1973).

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

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

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

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

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3. Geological setting

The Afro-Arabian rift system is extending from Turkey to Mozambique (McConnell and Baker, 1970) and is the current episode of the Phanerozoic break-up of the East African continental plate (Bosworth, 2015). It contains the rifting in the Gulf of Aden, in the Red Sea and in East Africa. In the center of that system, the Ethiopian northwestern and southeastern plateaus represent an elevated topography with a highest peak of 4,620 m (Ras Dashan) and an average elevation of 2000 m above sea level. This area is part of the so-called African Superswell, a wide region of anomalously high topography comprising East Africa (Lithgow-Bertelloni and Silver, 1998; Corti, 2009). In western Yemen, the Sarawat Mountains are the highest peaks in the Arabian Peninsula, reaching more than 3,000 m, at only 100 km from the shoreline of the Red Sea. The mountains show a typical stair morphology with steep slopes at the western and southern sides, while the eastern side of the mountains slopes downward more gently.

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

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

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

The Afar triangle is the region where the above mentioned three rift arms meet (Fig. 3). It is considered as a geological depression as it is an area of low elevation compared to the high Ethiopian plateaus, and thus commonly referred to as the Afar 'depression'. Nevertheless, this term is misleading as the Afar triangle is included within the rifted area and is geologically elevated from the deep bathymetry of the Gulf of Aden and the Red Sea basins. The Afar triangle is mainly floored by Pliocene and younger volcanic rocks, where Miocene volcanic series are exposed along the western margins and at the elevated Danakil block. It comprises many volcanoes that compose axial volcanic ranges (Fig. 2), where the Red Sea side is characterized by transverse volcanic fields and the southern side by central volcanoes (Varet, 2018). Two magnetic isochrons have been recognized in the Tendaho graben, indicating young oceanization in central Afar (Bridges et al., 2012). Structurally, several mega-scale accommodation zones connecting the different rift segments and a triple junction location is recognized at 11.0°N, 41.6°E at the Tendaho-Goba'ad Discontinuity (e.g, Tesfaye et al., 2003) (Fig. 3).

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4. Temporal constraints

4.1. Flood basalts and uplift

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

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

4.2. Gulf of Aden

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

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

4.3. Red Sea

It is not certain when continental rifting in the Red Sea began; however, sedimentary sequences suggest it postdates rifting in the Gulf of Aden by a few million years (Bosworth et al., 2005). Independent evidence suggests that rifting had begun simultaneously along the entire Red Sea at late Oligocene-Early Miocene, ~23 Ma (Plaziat et al., 1998; Szymanski et al., 2016; Stockli and Bosworth, 2018; Morag et al., 2019). Magnetic isochrons associated with seafloor spreading are only known from the southern parts of the Red Sea. However, oceanic lithosphere is probably abundant along most of the basin (Augustin et al., 2021). Chron 3 (4.2 Ma) is only present between latitudes 16° and 18°, while chrons 2A (2.6 Ma) and 2 (1.8 Ma) are present up to latitude 22° (Schettino et al., 2016). Structural reconstructions, geodetic measurements, and magnetic stripes suggest opening rates of ~11 mm/yr in the central parts of the basin, with an abrupt increase at ~5 Ma (Fig. 4) (Schettino et al., 2018). The southern edges of the magnetic chrons suggest that the ridge rapidly propagated southwards, with rates of ~30 mm/yr, between chrons 3 (4.2 Ma) and 2A (2.6 Ma). However, the rapid propagation was halted in the last 2.6 Ma (Fig. 3).

4.4. Main Ethiopian Rift

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

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

5. Data and Methods

We used bathymetry and topography data to identify morphotectonic features. To highlight and map the architecture of the margins and axes of the rifts we applied the Difference of Gaussians method to the topography and the bathymetry grids (Akram et al., 2017). This method allows a fast and accurate edge detection of elevation using active spatial bandpass filtering. We applied luminance coloring to the resulted grid using the open-source image processing software, Gimp.org.

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

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

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

6. Results

6.1. Rift margins

The most prominent morphological feature of the rift system is the sharp cliff along its shoulders. The shoulder cliffs mark the rift margin as they distinguish between (1) uplifted pre-rift rocks of the Arabo-Nubian shield or trap basalts sequences and (2) Quaternary arid fluvial sediments or young volcanic sequences. Thus, the shoulder cliffs have a very distinctive appearance in the topographical and gravity data. The edge detection analysis of topography and bathymetry data allows us to outline the rift margins (Fig. 6).

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

In the Gulf of Aden, the shoulder cliffs generally follow the trend of the basin. In the western parts the shoulder cliffs are less straight and less continuous than those of the Red Sea and generally reflect the sinistral basin structures. This morphology is well explained by oblique rifting along the Gulf of Aden (Leroy

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et al., 2013). The average rift width in the study area is 470 ± 45 km (calculated rift-perpendicular), with a general eastward increase (Fig. 6b). We recognize an abrupt change in rift width along three lines (III-V in Fig. 6), which are associated with fracture zones. Along the Somalian margin prominent sinistral offsets are recognized along lines III and V. This cliff segment is a morphological continuation of the Tendaho-Goba'ad Discontinuity lineament, and is also prominent in the VGG map (Fig. 5a).

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

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

6.2. Rift axes

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

The rift axis along the Red Sea is outlined by a deep and wide axial trough that ends at latitude 14.5°, approximately 400 km from the triple junction (Fig. 7a). South of latitude 14.5°, we find geophysical evidence that the rift axis is bent, entering the Afar region at the Bay of Beylul (latitude 13.3°): (1) The VGG signature of the Red Sea axis, with highs along the walls of the axial trough and a low above the center (Fig. 7b and profile B). (2) A trail of volcanic islands follows its path (Hanish-Zukur Islands; Fig. 3). (3) A general trend of recent onshore magmatism meets this line at the Bay of Beylul (Fig. 3). (4) This line also best fits GPS based rigid block model (Viltres et al., 2020). In addition to this segment, a typical gravity signature of the rift axis with a central BGA high and VGG picks to its side, is also recognized along the connection of the Red Sea with the Gulf of Aden at Bab al Mandab Strait (latitudes 13.2° to 12.3°; Fig. 7 profile CC'). Nevertheless, this segment is not an active rift axis as no earthquake, volcanic or bathymetrical expression is associated with it (Fig. 3).

In the Gulf of Aden, there is also a distinct change in the rift axis characteristics, approximately 400 km from the triple junction (Fig. 8). Up to the Shukra al Sheik discontinuity, the Gulf of Aden is a deep basin, reaching depths of more than 1,000 m only a few kilometers from the shore, and has a fragmented axial trough, offset by oblique left-lateral transform faults. West to the Shukra al Sheik discontinuity, the basin is shallow, and the axial trough is very distinct, characterized by deep and sharp morphology. This ~400 km long curved segment of the axis impales the Afar triangle at the Gulf of Tadjoura (Djibouti). This axial segment has a distinct gravity signature and is characterized by intensive seismic activity, perhaps the most intensive in the rift system, with over 1000 recorded events with magnitude above 4ML (ISC catalogue).

In the Main Ethiopian Rift, there are no abrupt changes in the characteristics of the rift valley with the proximity to the Afar triangle (Fig. 9). Instead, the rift valley goes through an elevated dome peaking approximately 400 km from the triple junction (Fig. 9a). The along-strike profile (profile B in Fig. 9) shows that the rift valley reaches altitudes of more than 2000 m and is associated with a BGA low.

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

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

7. Discussion

7.1. The architecture of the intersection region

The Afar triangle is the intersection region of three rift arms, the Gulf of Aden, the Red Sea and the Main Ethiopian Rift. Far from the intersection region, the axes and margins of these rifts follow a general parallel trend suggesting that rigid plate tectonics of the Nubian, Arabian and Somalian plates controlled their structural development (Garfunkel and Beyth, 2006; Reilinger et al., 2006; Reilinger and McClusky, 2011; Schettino et al., 2018). Within the Afar triangle, southwest to the Tendaho-Goba'ad discontinuity, the rift margins are continuous and smooth, and the axial volcanic range generally continues the trend of the axial valley of the Main Ethiopian Rift, reflecting a sub-perpendicular extension in accordance with the Nubia – Somalia kinematics, and thus, could be regarded as a rigid plate boundary. However, the architecture of the intersection region northeast to the Tendaho-Goba'ad discontinuity is more complex and is not simply resolved by rigid plate kinematics (Garfunkel and Beyth, 2006). Fig. 11 summarizes the rift margins and the axial segments mapped in this study. The rift axes of the Gulf of Aden and the Red Sea abruptly change their characteristics, particularly their trends, with the proximity to the Afar region. Around ~400 km from the triple junction, both the Gulf of Aden and the Red Sea axes deviate from their basin parallel trend, bending towards the third and younger arm of the Main Ethiopian Rift. The rift margins within Afar, northeast to the Tendaho-Goba'ad discontinuity, are fragmented, and there are multiple, short, and sub-parallel axial segments. Axial segments are generally sub-parallel to the Red Sea axis and not to the rift margins, which led authors to suggest that this region reflects an evolving discontinuity of the oceanic spreading center in the Red Sea (e.g. Tazieff et al., 1972; Bosworth et al., 2005). However, we don't find any evidence for a transform connection between the ridge in the Red Sea and the continuation of the northern Afar axial segments, offshore Gulf of Zula. Magnetic stripes in the Red Sea are observed at more than 200 km south of the Gulf of Zula region (Fig 12.), and the volcanic ridge in the southern Red Sea is very active (Eyles et al., 2018). Although earthquake clusters at latitude 16.5° indicate strike-slip solutions, supporting a structural connection to the Red Sea axis, these are abundant throughout the study area (Hofstetter and Beyth, 2003). Alternatively, it is possible to regard the jump between the Red Sea ridge to the axial segments in northeastern Afar as a non-transform discontinuity. However, second-order discontinuities are usually characterized by <30 km offsets, and here the jump is of ~200 km (Macdonald et al., 1984; Carbotte et al., 2016). Thus, we find no circumstantial evidence to regard the axial volcanism

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in the Afar depression as part of the development of the Red Sea spreading center. Our analyses suggest that the area northeast to the Tendaho-Goba'ad discontinuity is characterized by diffuse deformation, reflecting a rugged connection of the Red Sea and the Gulf of Aden arms to the Main Ethiopian Rift. Kinematic studies support this view, indicating that microplate rotations and diffuse boundaries significantly influence the structural development of this region. A recent model based on GPS observations (Viltres et al., 2020) reveals a diffuse character of the Danakil - Nubia boundary with inter-rifting deformation over more than 100 km wide zone. The Danakil microplate extends to Hanish-Zukur Islands at its southern edge (~13.8°N) with no precise/sharp boundary. The Danakil microplate is rotating counterclockwise (Manighetti et al., 2001), while the Ali-Sabieh block, south of the Gulf of Tadjoura, is rotating clockwise (Audin et al., 2004), described as a "saloon-doors" mode of opening (Kidane, 2016). Hence, the architecture of the intersection region of the rift arms discloses a ~150,000 km^2 complex region, in which the three rift arms are linked by diffuse boundaries and microplate rotations (Fig. 11). Accordingly, a truly single triple junction point, in the sense of a three-rift arms intersection point, cannot be specified for this system, and multiple triple junctions could be considered (e.g., see tectonic models in Viltres et al., 2020). Nevertheless, we agree that the intersection point of the Ethiopian rift valley and the Tendaho-Goba'ad Discontinuity could be regarded as the 'main' junction point of the rift system, as the deformation characteristics are most distinctively changed there (Tesfaye et al., 2003).

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

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

1) The first is the connection of the Main Ethiopian Rift to the Gulf of Aden-Red Sea rifts by a northeastward propagation. The margins of southeast Afar show symmetric, continuous, and smooth curved trends, from the elevated regions of the Main Ethiopian Rift to the Tendaho-Goba'ad Discontinuity (Fig. 6). The Somalian margin is curved clockwise, like the Ali-Sabieh sense of rotation (Kidane, 2016), whereas, the Ethiopian margin is curved counterclockwise, like the Danakil sense of rotation (Schult, 1974). This architecture could be understood in terms of fracture mechanics by reorientation of a propagating fracture in the vicinity of a pre-existing fracture. Strain analysis indicates that a propagating fracture would curve in parallel to the pre-existing fracture under tensional stress field due to free surface boundary conditions induced by the open pre-existing fracture (Dyer, 1988). Thus, this macro scale architecture may express a smooth linkage of the Main Ethiopian Rift to the pre-existing Gulf of Aden-Red Sea rifts by a northeastward propagation. Hence, this implies that a triple junction formed at a late stage, when all the three arms were already significantly developed. This conclusion agrees with structural geochronology within the northern Main Ethiopian Rift showing that extension in the northern Main Ethiopian rift commenced at 11 Ma (Wolfenden et al., 2004).

2) The second spatial constraint is an abandonment of an early tectonic connection between the Red Sea and the Gulf of Aden through Bab al-Mandab Strait. As the VGG and neovolcanic activity indicate that the Red Sea axis currently enters Afar at the Bay of Beylul (see section 6.2), we find arguments for an earlier tectonic connection between the Red Sea and the Gulf of Aden through Bab al-Mandab Strait: (i) Below latitude 13.2° and up to the connection to the Gulf of Aden (at latitude 12.3°), the gravity data shows typical rift axis characteristics, with BGA high and VGG picks to its side (Fig. 7 and Fig. 8; see section 6.2). (ii) Submarine channel north to the Hanish Island (latitude 13.4°) has no association with water currents and is best explained by subsurface rift structures (Mitchell and Sofianos, 2018). (iii) This is the straight continuation of the trend of the Red Sea axis, along which the basins are curtly connected (Fig. 1). Thus, it

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is reasonable that it was also the tectonic connection in the early stages of rift development. Likewise, reconstructions suggest that the Danakil microplate started to rotate in Oligocene-Miocene when Arabia was already separated from Africa (Collet et al., 2000). This suggests that the present deviation from the basin parallel trend of the rift axes at the tip of the Gulf of Aden and of the Red Sea marks a tectonic reorganization in this region.

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

7.3. Mechanisms for plume-rift association

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

Active models, on the other hand, are not in line with the progressive development of the rifts, mainly because the flood basalts region cannot be considered a center or a nucleus, from which rift arms spread, as expected in an actively generated triple junction. The triple junction was the last feature to develop in the system, by the propagation of the Main Ethiopian Rift towards Afar, followed by a tectonic reorganization including the abandonment of a former tectonic connection between the Red Sea and the Gulf of Aden. By this time, the rift arms were already developed and break-up was already accomplished between Africa and Arabia. This tectonic reorganization cannot be attributed to the development of gravitational potential by the plume head (Hill, 1991), as it occurred millions of years after flood basalts magmatism. That rules out the possibility that the onset of the triple junction was generated by the arrival of the Afar plume, as more than 20 Ma separate these events, and as the rift arms did not spread from the plume region.

We propose a scenario in which rifting was triggered by a plume-induced plate rotation (Fig. 2c). Numerical simulations suggest that horizontal asthenospheric flows due to the arrival of a plume-head at the base of the lithosphere induce a plume-push force that can accelerate plates by several cm yr^{-1} (van Hinsbergen et al., 2011, 2021; Pusok and Stegman, 2020). In this scenario, flood basalt volcanism would be synchronous to an abrupt plate speed-up and thus to new remote stress conditions. In the case of the

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Indian plate, at least two episodes of massive flood basalt volcanism, Morondava LIP (~94 Ma) and Deccan traps (67 Ma), are associated with plume derived plate acceleration, and a drastic change in the tectonic framework (van Hinsbergen et al., 2011, 2021; Cande and Stegman, 2011; Pusok and Stegman, 2020). Further, torque balance modeling suggests that horizontal plume-push can force a significant plate rotation and, consequently the initiation of new plate boundaries (van Hinsbergen et al., 2021).

In the Afro-Arabian rift, indeed new plate boundaries formed after the arrival of the large Afar plume and a significant plate rotation of Arabia around a nearby pole characterizes the Arabian continent (Joffe and Garfunkel, 1987; Viltres et al., 2022). Magnetic stripes and structural reconstructions suggest that the rotation around a nearby pole already characterizes Arabia since the Oligocene (Fournier et al., 2010; Schettino et al., 2018). Additionally, the beginning of intensive volcanism in the north-western Arabian plate (Harrat Ash Shaam) at Late Oligocene (Ilani et al., 2001), reflecting a change in mantle-crust interaction and in intracontinental extension within the Arabian plate, adjacent to the arrival of Afar plume (Garfunkel, 1989). In this large volcanic field, diking directions from Miocene to recent ages record the rotation of Arabia (Giannerini et al., 1988), suggesting that already during the first stages of volcanism the Arabian plate was rotating around a nearby pole. The arrival of the Afar plume was also accompanied by a slowdown of Africa (Le Pichon and Gaulier, 1988). By this time, Africa collided with Eurasia in the west, explaining its slowdown (Jolivet and Faccenna, 2000) and its increased intraplate volcanism (Burke, 1996). However, this collision of Africa and Eurasia cannot simply resolve the change in the rotation of Arabia as the Arabian continent collided with Eurasia no earlier than ~18 Ma (Su and Zhou, 2020), although some authors suggested that asymmetrical along-trench entrance of continental material could lead to an intraplate extension similar to those that generated the Africa-Arabia break-up (Bellahsen et al., 2003). Faccenna et al., (2013) already showed that plume-push from the Afar area resolves the present-day plate kinematics in the middle-east, particularly the anti-clockwise toroidal pattern of the Arabia–Anatolia–Aegean system. The importance of active upwelling in Afar to lateral mantle flow below Arabia is also illustrated by shear-wave splitting indicating a general N-S anisotropy in the mantle (Qaysi et al., 2018).

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

8. Summary and Conclusions

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

We highlight key differences in the terminations of the Gulf of Aden and the Red Sea arms, which are rough and irregular, versus the symmetric, continuous, and smooth architecture of the Main Ethiopian Rift. The architecture of the intersection regions allows us to infer two tempo-spatial constraints in the development of the rifts: (1) the connection of the Main Ethiopian Rift to the Gulf of Aden and to the Red Sea by its northeastward propagation, and, (2) the abandonment of an early tectonic connection between the Red Sea and the Gulf of Aden. These suggest a progressive development of the intersection area including a broad region of diffuse deformation and recent tectonic reorganization. The onset of the triple junction was the last feature to develop in the plume-rift system, after all rift arms were sufficiently developed and break-up was accomplished.

This progressive development is not in line with the classic active rifting model, which predicts a plume-generated triple junction at the locus of the rift, from which the rifts develop. Nevertheless, the classic passive rifting model fails to explain the chronological evidence as flood basalts probably erupted on elevated topography before rifting started. We discuss a scenario of plume-induced plate rotation in which the rotation of Arabia around a nearby pole was triggered by the arrival of the Afar plume. We demonstrate that the rotation of Arabia around a nearby pole characterizes the system since the Oligocene and reflects observed mantle flows below Arabia. We suggest that this scenario better explains the progressive development of the plume-rift system in the Afro-Arabian rift.

9. Data availability

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

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

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

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

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

10. Author contribution

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

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11. Competing interests

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

12. Acknowledgments

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13. Figure captions

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

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

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

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

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

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

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

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

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

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

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

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

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

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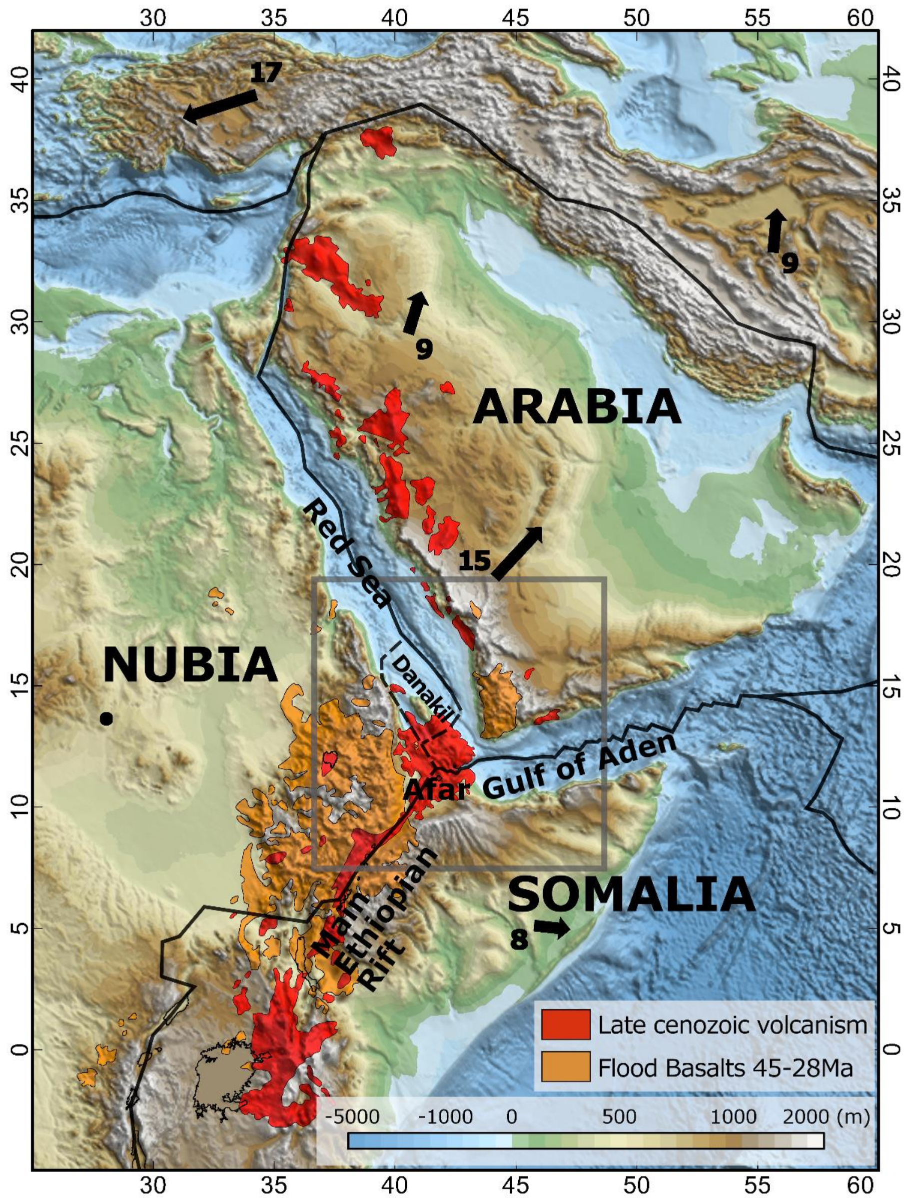

Figure 1. Elevation map of the study area, showing the general plate tectonic configuration (from USGS and from Viltres et al., (2020) in the Afar region) and Cenozoic volcanics (modified from Varet, 1978; Davison et al., 1994; Beyene and Abdelsalam, 2005; Bosworth and Stockli, 2016) Black arrows indicate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

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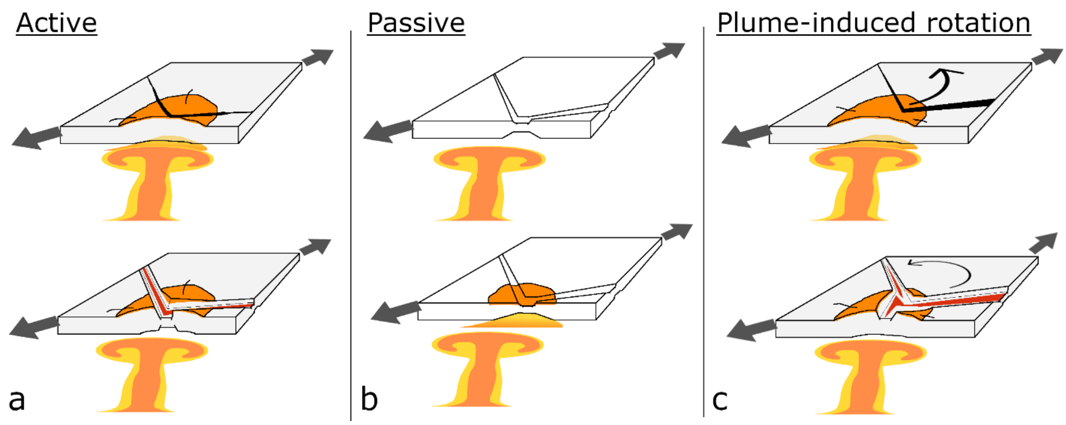

Figure 2. Schematic mechanisms for plume-rift association in the Afro-Arabian rift. (a) Active mechanism, in which rifting results from the actively rising head of the Afar plume. In this mechanism impinging and eroding the base of the lithosphere prompt uplift and decompression melting and flood basalts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

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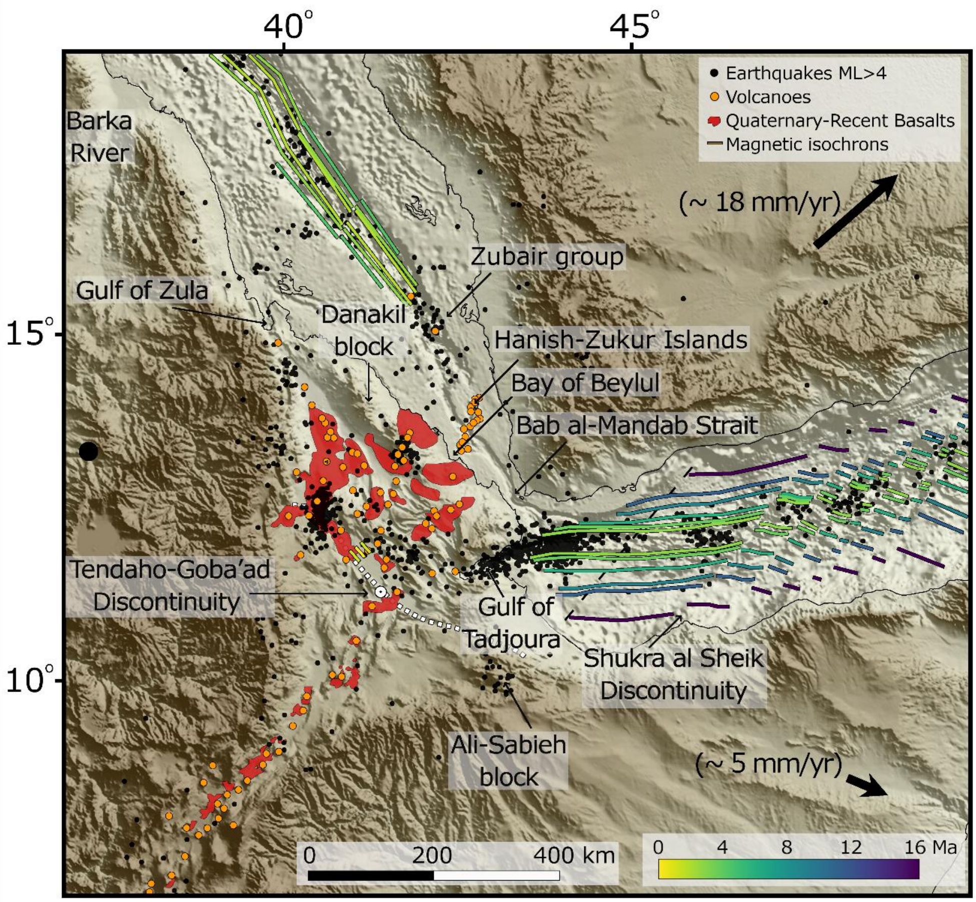

Figure 3. Map of the Afar region showing magnetic isochrons (modified from Fournier et al., 2010; Bridges et al., 2012; Schettino et al., 2016), earthquake locations (from ISC catalog), Holocene onshore volcano locations (from GVP catalog and Viltres et al., (2020)) and recent volcanism (modified from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

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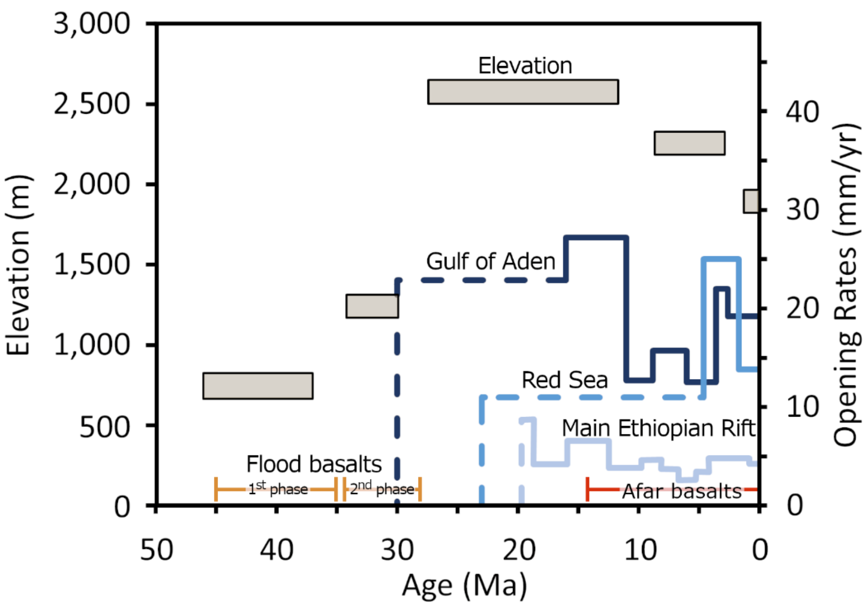

Figure 4. Elevation of the Ethiopian–Yemen plateau (after Sembroni et al., 2016; Faccenna et al., 2019), volcanic episodes and openinng rates of the rift arms (modified from Fournier et al., 2010; DeMets and Merkouriev, 2016; Schettino et al., 2018). Dashed lines indicate estimations from geological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

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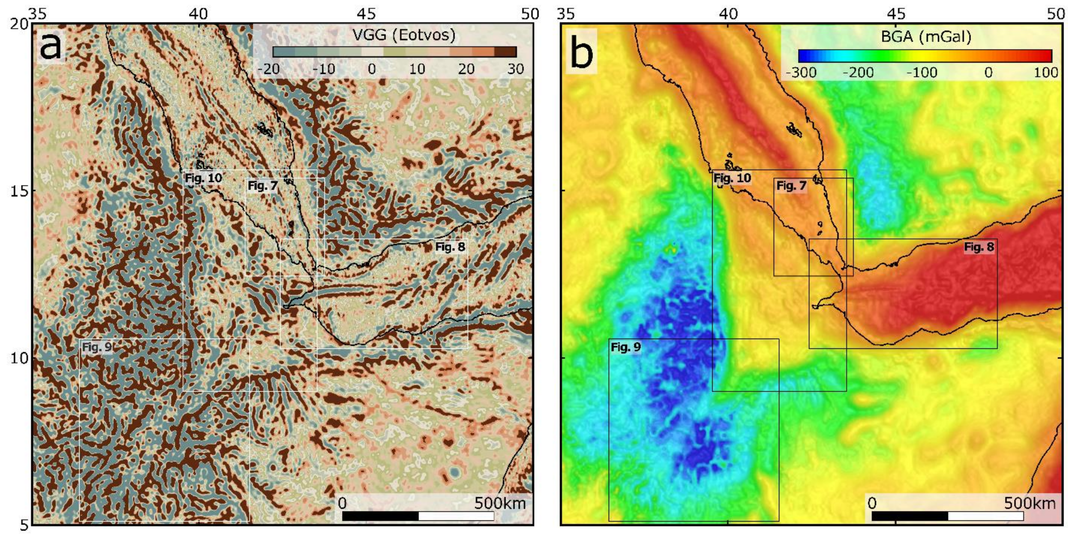

Figure 5. Gravity data of the Afar region. (a) Vertical gravity gradient from Sandwell et al. (2014). Bouguer anomaly model from ICGEM, XGM2019e (Zingerle et al., 2020).

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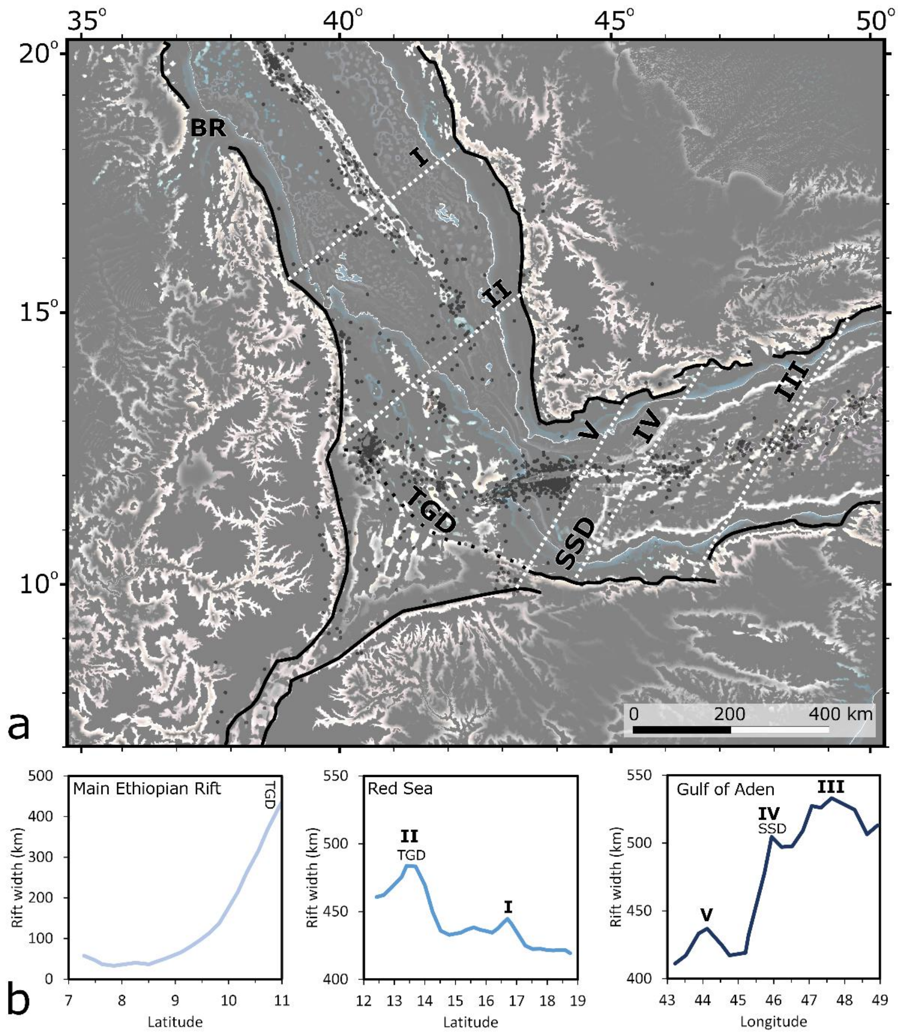

Figure 6. (a) Difference of Gaussians applied to topography and bathymetry showing rift margins (black lines). White dashed lines indicate peaks in rift width. TGD is the Tendaho-Goba'ad Discontinuity. SSD is the Shukra al Sheik discontinuity. Black dots indicate earthquake locations (ISC catalog). (b)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

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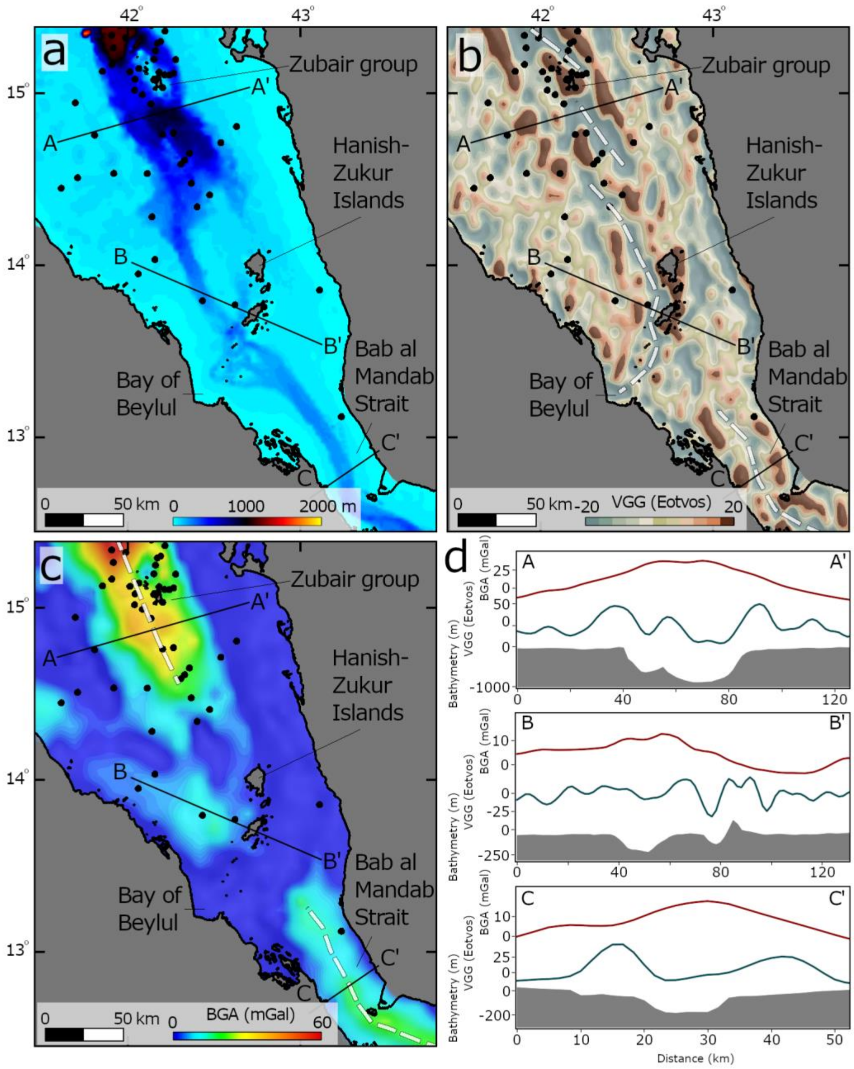

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900 **Figure 7.** Bathymetry (a), vertical gravity gradient (b) and Bouguer anomaly (c) in the southern Red Sea.
901 Black dots indicate earthquake locations (ISC catalog). (d) Profiles across rift axis.

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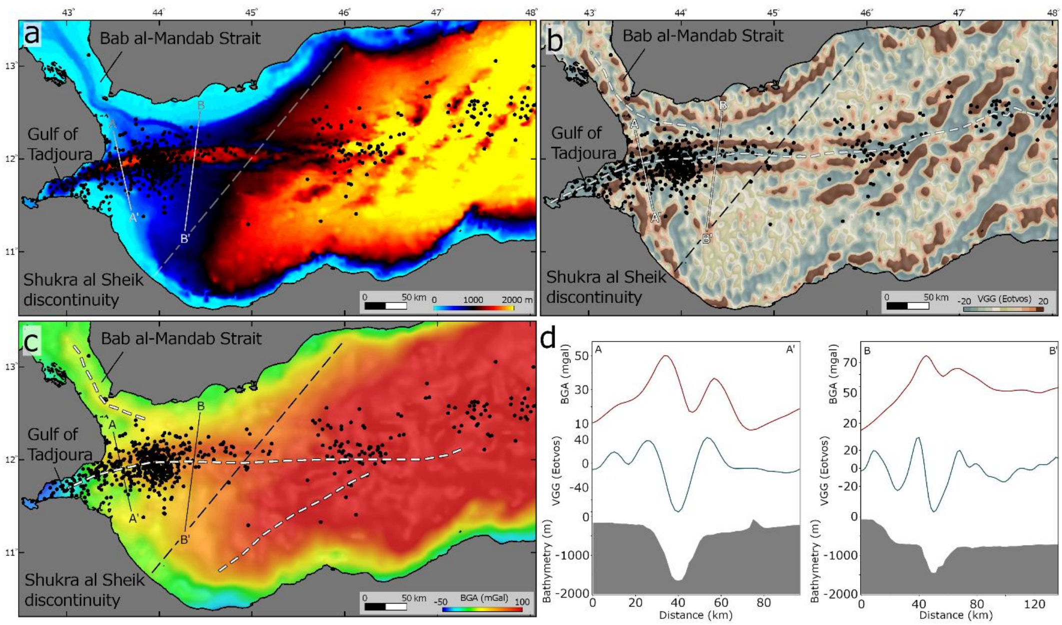
902 

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

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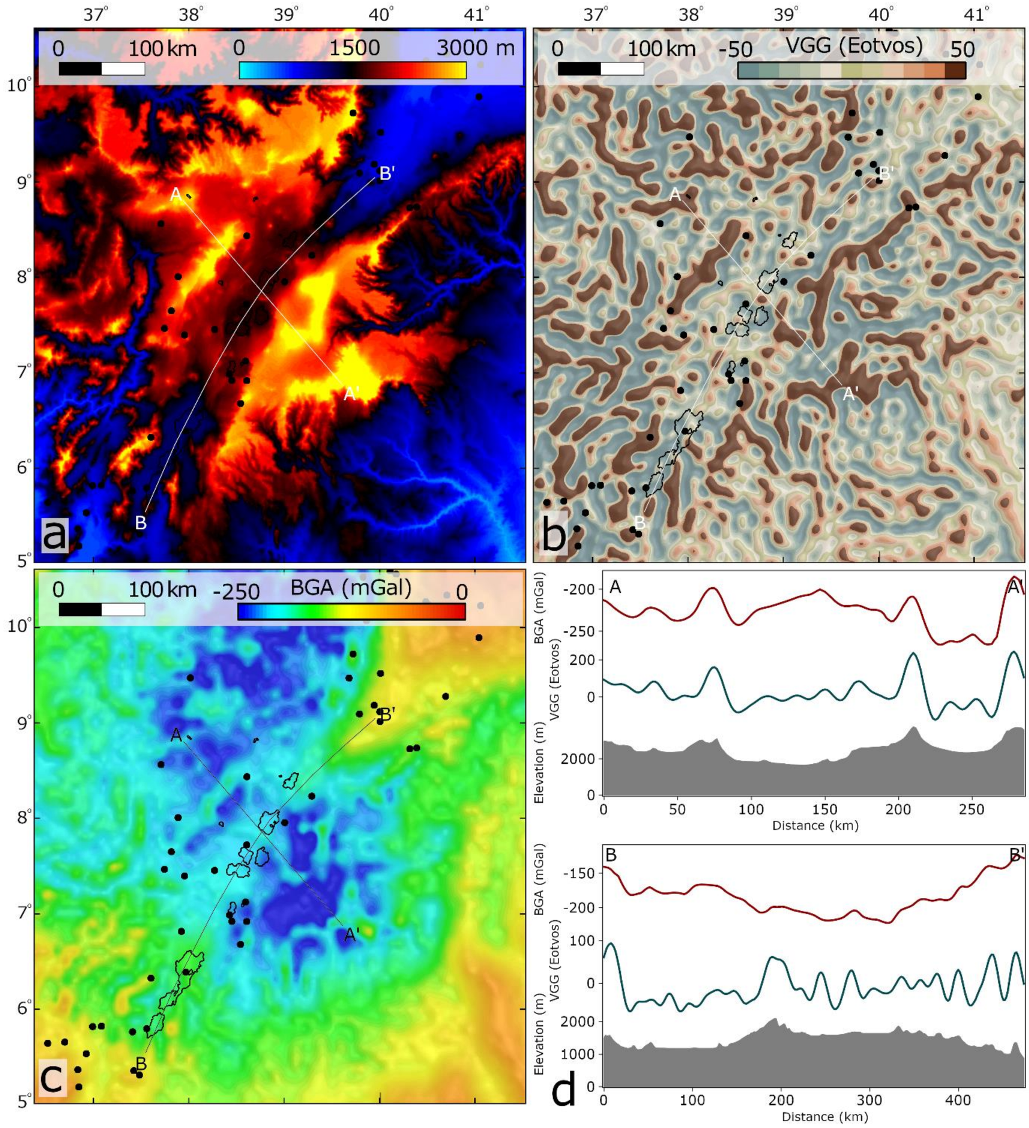

Figure 9. Topography (a), vertical gravity gradient (b) and Bouguer anomaly (c) in the northern Main Ethiopian Rift. Black dots indicate earthquake locations (ISC catalog). (d) Profiles across (AA') and along (BB') the rift valley.

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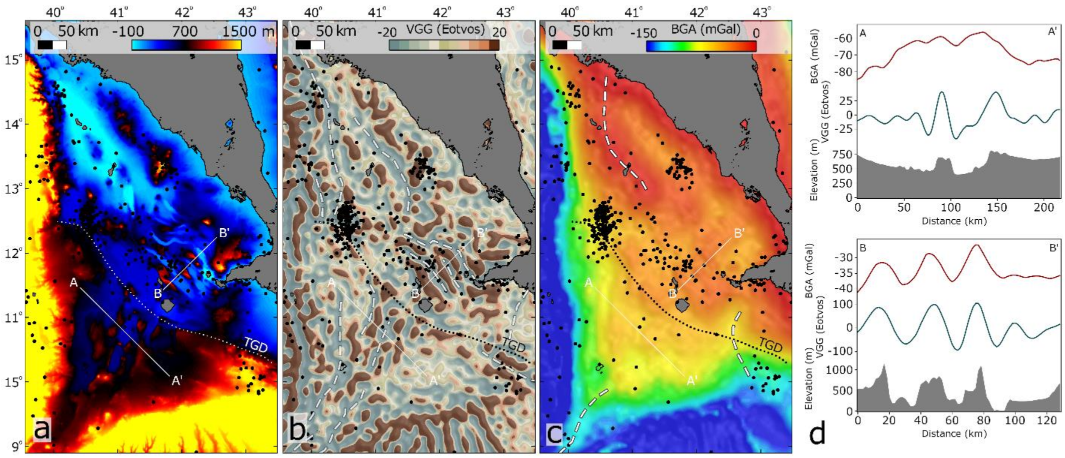

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910 **Figure 10.** Topography (a), vertical gravity gradient (b) and Bouguer anomaly (c) in the Afar triangle. Black
911 dots indicate earthquake locations (ISC catalog). TGD is the Tendaho-Goba'ad Discontinuity. (d) Profiles
912 SW (AA') and NE (BB')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

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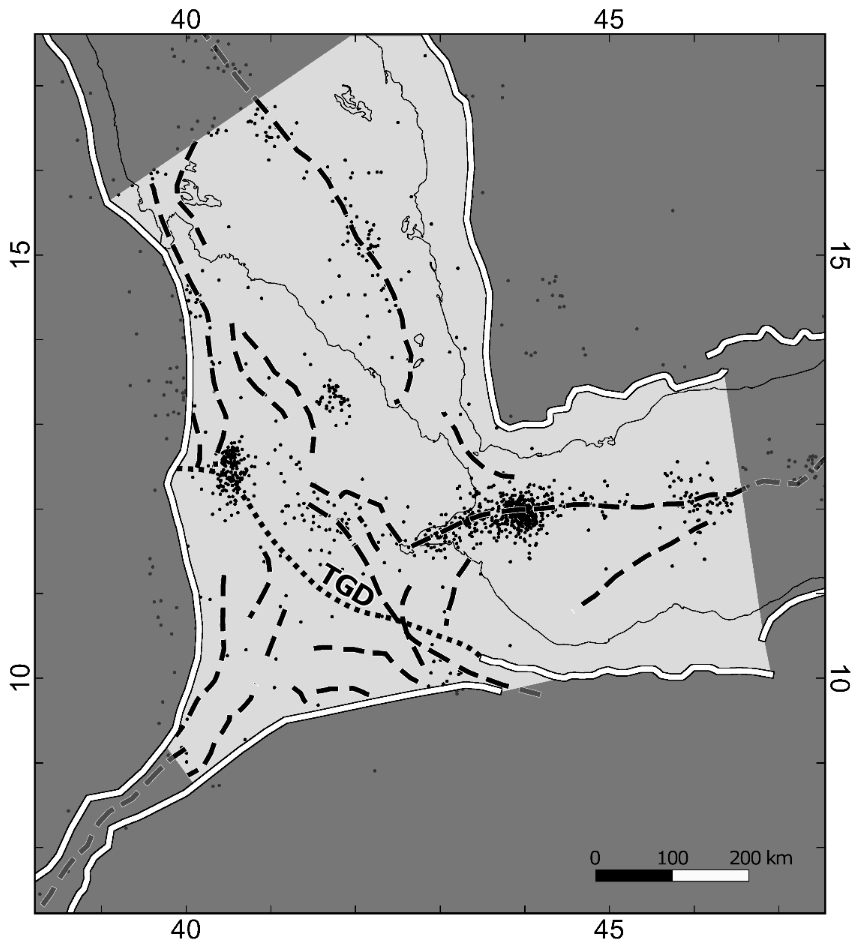

Figure 11. Rift margins (solid white lines) and axial segments (long dashed black lines) in the Afar region. Black dots indicate earthquake locations (ISC catalog). TGD is the Tendaho-Goba'ad Discontinuity.

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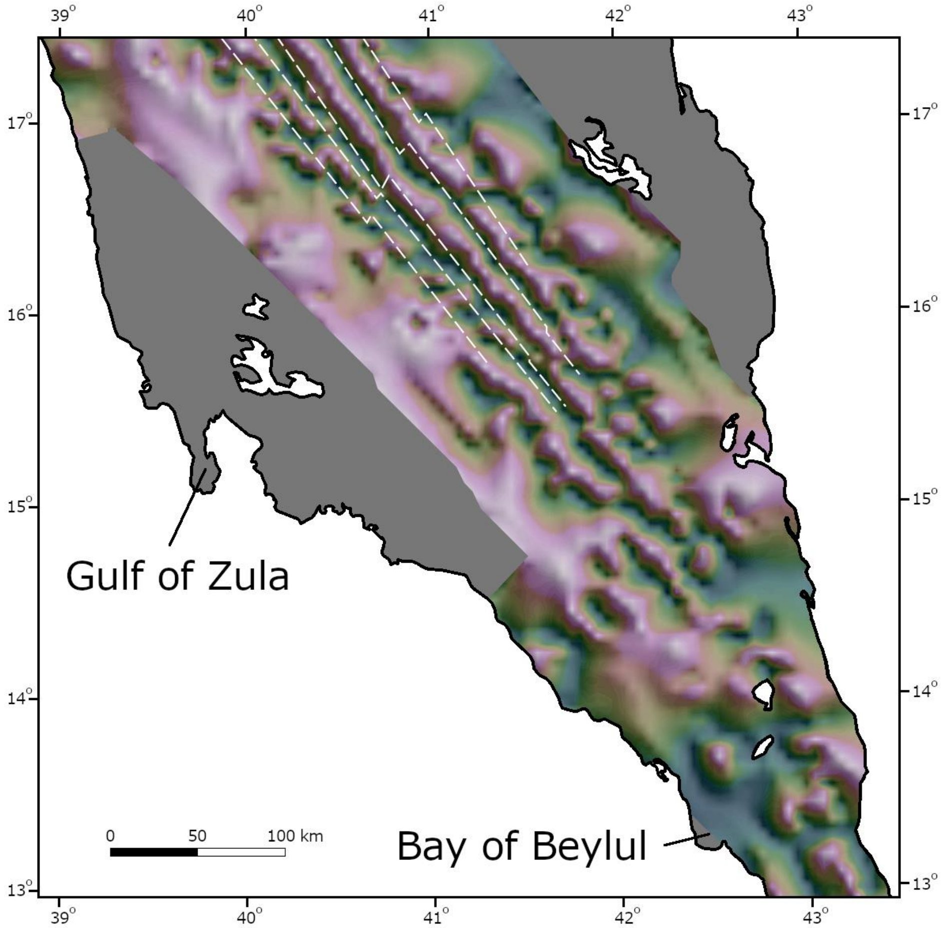

Figure 12. Tilt-angle derivative map of magnetic anomalies, projected on a shaded relief after Issachar et al. (2022). Purple colures represent positive angles and green colors represent negative angles. White dashed lines indicate magnetic stripes (Schettino et al., 2016).

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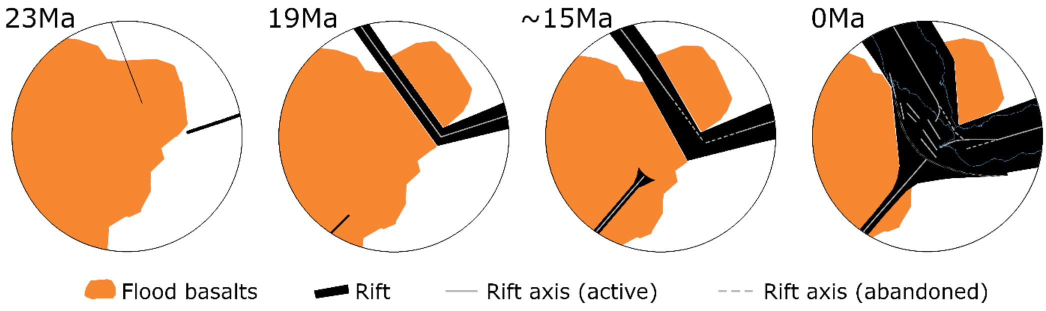

928 **Figure 13.** Synthesis of the progressive development of the rift intersections.