10/3/24

Dear Editor,

Please see our revised manuscript “Rift and plume: a discussion on active and passive rifting mechanisms in the Afro-Arabian rift based on synthesis of geophysical data”.

We carefully considered the comments and suggestions of the reviewers and community, and replied on the public discussion. We feel that the comments and following discussion were very helpful and improved the manuscript significantly.

In addition to our replies in the public discussion, for each comment of the reviewers you can find below our explanation of how we specifically revised the manuscript.

Figures 1, 3 and 11 are modified in the revised manuscript.

Hope you will find the revised manuscript suitable for publication in Solid Earth

On behalf all author,

Ran Issachar

Comment by Antonio Schettino:

R38-40: “Continental flood basalts (...) are associated with extensive volcanism during short time intervals, brought to the surface by deep-seated mantle plumes”. I am not sure that any LIP is associated with the presence of a deep mantle plume. The authors should consider at least the valuable contributions by Don Anderson (e.g., Anderson, 1994 ; Anderson, 2005).

- We changed the text accordingly and referred also to the contributions by Don Anderson.

R41-42: “Observations indicate a close temporal and spatial occurrence between the eruption of flood basalts and continental break-up”. Are the authors suggesting that any eruption of flood basalts is associated with continental break-up? As pointed out by Buiter & Torsvik (2014), this is certainly false.

- We modified the text to avoid confusion.

R42-44: “when reconstructed back to their original plate tectonic configuration, a R-R-R triple junction is found within the flood basalts areas”. This assertion is incorrect if considered as a general statement. We have examples of RRR triple junctions in magma poor conditions (e.g., in the southern North Atlantic during the Cretaceous).

- We modified the text to avoid confusion.

R70: “deep mantle convection and its interaction with the Earth’s crust”. It is more correct to say “Earth’s lithosphere”.

- We changed the text

R73-76: “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”. This is somewhat confusing. The first sentence seems to recover and accept Morgan’s (1971) proposal that “deep mantle convection has a significant role in accelerating the overlying tectonic plates”. The successive sentence recalls the contrasting modern view that the main driving force of plate tectonics is slab pull, but without citing Forsyth & Uyeda (1975) work. Finally, the last sentence, which starts with “Furthermore” but is unrelated to the previous sentences, suggests that plumes have a major role in plate tectonics because they are responsible for the weakening of the upper lithosphere. This seems to imply that in absence of mantle plumes we would have no weakening of the “upper lithosphere” (why “upper”?, does the lower lithosphere remain strong?). In reality, the continental litosphere is weak (and can be extended) because of the presence of water (for a short discussion on this point see Schettino & Ranalli, 2023). When a mantle plume is present, it causes thinning, that is, a rise of the isotherms, not weakening.

- We edited the text and removed the unrelated sentence to avoid confusion.

R127-128: “Six pairs of magnetic stripes are recognized along the Gulf of Aden ridge”. It would be more correct to avoid the textbook term “magnetic stripes” and use instead “magnetic anomalies”. Furthermore, it should be “the Gulf of Aden”, not “the Gulf of Aden ridge”.

- We changed the text.

R148-160: “Two magnetic isochrons have been recognized in the Tendaho graben, indicating young oceanization in central Afar (Bridges et al., 2012)”. This is really a stretch of Bridges’s et al. (2012) thinking. It seems that the authors have mis-interpreted the important results of Bridges’s et al. (2012) paper.

- We understand and agree. We modified the text.

R179: “no recent data was published”. It should be: “no recent data were published”.

- We changed the text.

R209-211: “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”. I don’t understand this observation. The Red Sea ridge is composed by two independent branches. The southern ridge separates Arabia from Danakil with a rotation pole that is located in the Gulf of Aden. Consequently, the linear velocity increases northwards and the ridge propagated southwards, as correctly stated by the authors. However, the northern ridge separated Arabia from Nubia about a pole that is located ~50 km south of El Alamein. Therefore, in this case the linear velocity increases southwards and the ridge propagated northwards. Incidentally, I also note that this manuscript does not attribute much importance to the role of Danakil.

- We understand the point and agree. We changed the text.

R289-290: “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°)”. This is a very questionable interpretation. In my opinion, although Fig. 7a and 7b show the presence of two transform segments (in SW-NE direction), the rift axis does not enter the Danakil microplate and continues in SSE direction. The proposed boundary of the Danakil plate shoud be justified by new fieldwork, because simple visual analysis of geophysical maps could not be convincing for many readers.

- We added new geological evidence of volcanic cones and vents orientations in the Hanish islands to support the geophysical interpretation.

R297-298: “Nevertheless, this segment is not an active rift axis as no earthquake, volcanic or bathymetrical expression is associated with it (Fig. 3)”. This is not an argument, as the velocity of separation between Arabia and Danakil is very small in this area (less than 10 mm/yr) and very oblique with respect to the axis. I tested the possibility of a NE–SW strike–slip structure that transfers extension from the Red Sea ridge to Afar through Danakil but any kinematic test failed (this is discussed in Schettino et al, 2016).

- We modified the text and added points raised by the reviewer in the discussion.

R332-334: “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”. Clearly, a region characterized by stretching and rifting cannot be described in terms of rigid rotations. People involved in plate kinematics studies use rigid rotations to describe the motion of plate interiors, not of deforming margins.

- We agree, but this is a very broad region. This citation is from Garfunkel and Beyth (2006).

R340-342: “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”. I don’t understand this sentence.

- We rephrased the text.

R342-344: “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”. This sentence is also confusing. E-W dextral strike-slip faults in the area north of the Gulf of Zula are documented by several CMT fault plane solutions.

- We edited the text.

R396-397: “reconstructions suggest that the Danakil microplate started to rotate in Oligocene-Miocene when Arabia was already separated from Africa”. This timing is strange. According to several kinematic models (including the ones proposed by me) and to geological evidence, rifting between Arabia and Nubia started between 30 and 27 Ma (early Oligocene), while the Danakil and Sinai microplates formed during the Langhian (~14 Ma) by strain partitioning.

- We apologies for the mistake and corrected the text.

R432: “We propose a scenario in which rifting was triggered by a plume-induced plate rotation”. This is incorrect. Rifting in the Red Sea and the Gulf of Aden was triggered by far-field forces as any other process of continental breakup, although the presence of a mantle plume has certainly exerted some influence on the formation of a triple junction and the separation of Somalia from Nubia.

- There is no controversy, this is the point. The “plume-induced plate rotation” mechanism suggest that far field forces are increased by the plume-push. Still, the far field forces are the one that derive riffing.

<u>Comments by Derek Keir</u>

Line 76 - should upper lithosphere be lower lithosphere? The plume impacts the lower lithosphere first.

- We changed the text.

Line 95 - earth should be upper case Earth

- We changed the text.

Line 108 - 114 and section 7.3 - i thought a weakness of the work is lack of discussion of quite a bit of geodynamic modelling work on a similar topic to the aim of this discussion paper.

This manuscript has avoided discussing the various models by Stamps for the region in which GNSS, topography and lithosphere and asthenosphere imaging data have been used to guide numerical simulations to isolate driving forces of extension in NE Africa. These works generally found the gravitational potential energy (GPE) from uplift is a major driver of extension, with base of lithosphere traction rather minimally involved.

For example see Stamps et al., 2014 - https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2013JB010717

From what i can see the work by Stamps is somewhat in contradiction to the interpretations being made in the new discussion manuscript. This is fine - but i think the text deserves dealing with this in a more convincing fashion.

- We added a discussion in section 7.3

Line 141 - 152 - there is a fair body of literature in Afar and rifted margins more generally that discusses the concept that magnetic stripes could form as a result of magma intrusion and volcanism before the continental lithosphere is fully split - ie magnetic striping on the continnet ocean transition, and subtly prior to full seafloor spreading. This is potentially important for interpretting the onset of seafloor spreading. See section 5.1 of Ebinger et al., 2017 - especially the last paragraph of this and references therein https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2017TC004526

- We modified the text.

line 223 - replace "last" with "the early"

- We changed to "late"

Line 247 - Please double check this is a catalog of Quaternary volcanoes , rather than just Holocene volcanoes . Also google earth should be Google Earth

- Thanks, we used the Holocene catalog from Smithsonian.

Section 6 - consider using the term "escarpment" rather than sharp cliff / cliff. Escarpment is the more globally used term for these topographically prominent rifted margins.

- We changed the text.

End of section 7.1 - i saw this same point mentioned in one of the other reviews. The concept that strain in Afar is commonly somewhat localised in distinct rift segments but which are set within quite a broad strain field influenced by all the plate motions is not new. e.g. Keir et al., 2010, Tectonics identified a SE-NW striking dike intrusion event in the MER that coupled with structural geology and focal mechanisms, amongst other things, was used to interpret that strain from the NE motion of Arabia occurs in the MER of southern Afar. Also see Doubre et al., 2017 GJI and Pagli et al., 2019 which provide good evidence from geodesy for broad extension in central Afar. See Maestrelli et al., 2022 Tectonics for analog models that use a number of model scenarios to reconstruct potential evolution and distribution of extension and faulting of Afar. These models invoke somewhat broad zones in which extension from the various plates interact, and within which strain has a higher gradient (more localised) in some zones.

- We added a discussion in Section 7.1