nature portfolio

Peer Review File

New 40Ar-39Ar dating of the Afar Stratoid series shows progressive rift localisation in Afar (Ethiopia)

Corresponding Author: Dr Gianmaria Tortelli

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Dr Tortelli,

We apologize for the delay in sending this letter. Your manuscript titled "New 40Ar-39Ar dating of the Afar Stratoid series shows progressive rift localisation in Afar (Ethiopia)" has now been seen by 3 reviewers, and we include their comments at the end of this message, together with 2 attachments. They find your work of interest but rise some critical points. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider a revised manuscript before we make a final decision on publication.

As editorial threshold, we ask you to:

- Restructure your introduction and discussion to frame your study within the regional geological context.

- Fully justify the selection criteria of the literature K/Ar data used (and discarded) to build the presented model.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

Please submit your point-by-point responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:
Link Redacted
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Maria Laura Balestrieri
External Editor
Communications Earth & Environment

Carolina Ortiz Guerrero, PhD (she/her/ella)
Associate Editor
Communications Earth & Environment

EDITORIAL POLICIES AND FORMATTING

We ask that you ensure your manuscript complies with our editorial policies. Please ensure that the following formatting requirements are met, and any checklist relevant to your research is completed and uploaded as a Related Manuscript file type with the revised article.

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Furthermore, please align your manuscript with our format requirements, which are summarized on the following checklist:
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*** DATA: Communications Earth & Environment endorses the principles of the Enabling FAIR data project (http://www.copdess.org/enabling-fair-data-project/). We ask authors to make the data that support their conclusions available in permanent, publically accessible data repositories. (Please contact the editor if you are unable to make your data available).

All Communications Earth & Environment manuscripts must include a section titled "Data Availability" at the end of the Methods section or main text (if no Methods). More information on this policy, is available at http://www.nature.com/authors/policies/data/data-availability-statements-data-citations.pdf.

In particular, the Data availability statement should include:
- Unique identifiers (such as DOIs and hyperlinks for datasets in public repositories)
- Accession codes where appropriate
- If applicable, a statement regarding data available with restrictions
- If a dataset has a Digital Object Identifier (DOI) as its unique identifier, we strongly encourage including this in the Reference list and citing the dataset in the Data Availability Statement.

DATA SOURCES: All new data associated with the paper should be placed in a persistent repository where they can be freely and enduringly accessed. We recommend submitting the data to discipline-specific, community-recognized repositories, where possible and a list of recommended repositories is provided at http://www.nature.com/sdata/policies/repositories.

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Please refer to our data policies at http://www.nature.com/authors/policies/availability.html.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

I would recommend acceptance of the work with moderate/minor reviews. Most of which is in the organization and topics covered in introduction, as well as opening to a more regional context in the discussion. My main comments are below and I also commented directly on the manuscript.

* What are the major claims of the paper?
This paper presents new research on the Afar Depression in Ethiopia, a region characterized by active continental rifting. The authors use new 40Ar-39Ar dating of volcanic rocks synthesize this data with existing geochronological and geochemical information to reconstruct the temporal and spatial evolution of the rift, focusing on the Stratoid series, a large suite of volcanic rocks erupted between 4.5 and 0.88 million years ago. They find that the rift experienced a process of asymmetric localisation, narrowing progressively from a wider zone of extension to a more focused magmatic segment, while also migrating northward. This localization, the researchers argue, is driven primarily by plate motion rather than a deep mantle plume. The researchers also observe a geochemical signature suggesting that the magmatic system became shallower and more complex during localization, consistent with thinning of the lithosphere and the formation of shallow magma chambers.

* Are these claims novel, and will they be of interest to others in the community? If the conclusions are not original, it would be helpful if you could provide relevant references.
This comprehensive dataset allows them to propose a model for rift evolution and volcanic activity that challenges previous interpretations. Indeed, they propose that this rift localization, rather than being driven by a mantle plume, is primarily caused by the divergent motion of the Arabian and Nubian plates. Moreover, this work provides one of the most precise spatio-temporal constraints on rift localization. Overall, this study provides new insights into the dynamics of continental rifting and the role of tectonic forces versus mantle plumes in shaping the volcanic landscape. Even if these claims are not novels (e.g. Rychert et al 2012), the topic is controversial, and they bring new petrographic, geochemical and chronological evidence which will be of great interest to the community.

* Is the work convincing, and if not, what further evidence would be required to strengthen the conclusions?
I'm not a geochemist and I'm not able to judge the pertinence and quality of the data. However, the method used is very standard and I don't see any odd or incoherent age when compared to available data in the bibliography. Moreover, the method is carefully explained and all the raw data is made available for anyone who wishes to reproduce and check the results.

* On a more subjective note, do you feel that the paper will influence thinking in the field in terms of either conceptual understanding or technological capability? Please feel free to raise any further questions and concerns about the paper.
I find this paper interesting as it provides new and qualitative data on AFAR volcanism. Moreover it provides great insight in rift localization and rift evolution in this complex area. I would however point out that it lacks the regional context, which I think should be developed in the introduction with appropriate references (i.e. the work of Wolfenden is cited in introduction for Arabia-Nubia separation when it focuses only on Nubia-Somalia separation). In that regard, I think a more thorough and precise, yet brief paragraph on the regional geology is needed in the introduction. It would allow to discuss the implications of the evolution of rift localization and timing in regards to the complex Red Sea-Aden-EARS triple junction. The authors could also have a look at the paper by De Chabalier and Avouac (1995: Kinematics of the Asal rift (Djibouti) determined from the deformation of Fieale Volcano), where they suggest that decompression melting due to lithospheric thinning dominates the processes, and discuss how does this differ from the Tendaho-Dabbahu Manda Hararo segment?
I would also consider discussing the results in regard of the (very) new paper of Ben Mather (Spreading ridge migration enabled by plume-ridge de-anchoring, Nature Communications),
On a more formal note, I find the use of abbreviation excessive and exhausting, if in some cases justified, it should not be systematic.

Reviewer #2 (Remarks to the Author):

Dear Editor,
In their contribution entitled New 40Ar-39Ar dating of the Afar Stratoid series shows progressive rift localisation in Afar (Ethiopia), Tortelli et al. use the distribution, ages and geochemistry of extrusive lava series in the region of Afar to deduce that (1) extension is accommodated by rift localization rather than steady-state magmatic accretion; and (2) the melting source of magma is becoming shallower with time. Based on these conclusions, they assert that the magmatic activity observed in the Afar region is unlikely to be related to a plume and suggest that it is rather linked to the extensional plate tectonic settings.
First, I must state that I am neither a specialist of thermochronological methods, nor of the Afar study area, and hence I have not judged these aspects of the manuscript. This said, I found the data and their interpretation presented in the study convincing. This study is of interest for a broad range of earth scientists. Questions related to the importance of plumes in magma-rich rift systems are timely, and the new data and more importantly the new look provided by this study to feed this heated debate are welcome. The figures are relevant, clear and readable. The manuscript is well referenced and includes

recent studies.
My main concern about this contribution relates to the clarity of the used terminology and concepts. Some terms are not of common use (e.g., “rift spreading”), and yet they are not defined. Other definitions are awkward (e.g. “Asymmetry in rates but with the total still equal to the full spreading rate implies asymmetric spreading”). A definition of what the author mean with “crust” would also be welcome: is it fully continental (pre-rift) crust? Fully newly created magmatic crust? Partially continental and partially magmatic crust? This contribution would also benefit from a clearer and more concise presentation of the scientific question guiding this study, and a better highlight of its results in the Abstract and/or Introduction sections.

Please find below my detailed comments:
Abstract
Line 20: why mentioning the Wilson Cycle? It is not relevant to this study.
Line 24-25: the term “in-rift localisation” is very uncommon, it merits to be defined.
Line 27-28: “changes in the spatio-temporal distribution of volcanism and erupted lava volumes during rift localisation can be induced by plate motions”. Awkward statement, consider rewording.
Isn’t the conclusion that Afar shows rift localization rather than magmatic accretion a result of this study? If so, it merits to be presented as such in the abstract.

Introduction:
Line 32: “rifting and break-up is commonly associated with a mantle plume” I suggest tempering this statement since recent studies tend to support the converse is true (e.g. Sauter et al., 2023; Scientific Reports; 13:1195; https://doi.org/10.1038/s41598-023-28364-y)
Line 42: “Dalha” is labelled “Daha” in Fig. 1.
Line 47: “the main graben faults” are not labelled in fig. 1
Line 52: when extension is still going on in this direction replace “has occurred” by "has been occurring"
Line 53: “The crust is generally around 25-30 km thick”. Do you mean fully continental crust, fully magmatic crust, partially continental and magmatic or crust of unknown origin?
Line 54-55 you write “Extension in Afar started 55 at ~29-25 Ma” and then at Line 56 “Starting at ~4.5 Ma, extension has instead…” please clarify.
Line 63: “Stab et al. interpret…” please add the publication year.
Line 66-67: “a spreading centre-like scenario”. Please clarify: do you mean that continental extension if fully accommodated by magmatic accretion?
Line 77-78: “rift localisation and rift spreading”: please clarify what you mean with both terms.

Results:
Line 158: what does “m.a.s.l.” stand for?
Line 184-194: This paragraph presents a key point of your interpretation, and hence it would merit to be clarified. Why does rift localization imply a greater extension rate compared to magmatic spreading? When you refer to spreading, do you imply steady-state/constant rate magma accretion or can the accretion rate vary with time?

Figures:
Fig. 1: I suggest increasing the size of panel b compared to panel c since there is much more to read in the former compared to the latter.
Fig. 2: in panel c, you may want to specify that the different colored boxes represent the extended area during a given time period.

Reviewer #3 (Remarks to the Author):
Please see attached file

Version 1:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Dr Tortelli,

Your revised manuscript titled "New 40Ar-39Ar dating of the Afar Stratoid series shows progressive rift localisation in Afar (Ethiopia)" has now been seen by our original reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewer #3. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

EDITORIAL REQUESTS:

Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table".

*****Please take care to match our formatting and policy requirements. We will check revised manuscript and return manuscripts that do not comply. Such requests will lead to delays. *****

Please outline your response to each request in the right hand column. Please upload the completed table with your manuscript files as a Related Manuscript file.

If you have any questions or concerns about any of our requests, please do not hesitate to contact me.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Maria Laura Balestrieri
External Editor
Communications Earth & Environment

Carolina Ortiz Guerrero, Ph.D.
Associate Editor,
Communications Earth & Environment
Consulting Editor, Communications Sustainability

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I find the work compelling, interesting and innovative. The authors responded to my comments thoroughly and with clarity. I have nothing further to add, good work.

Reviewer #2 (Remarks to the Author):

Dear Editor,

The authors have effectively clarified the points I was concerned about, and hence I recommend acceptance.

Best regards

Reviewer #3 (Remarks to the Author):

I acknowledge the replies to my review and changes made in the text. I have just a couple of brief notes.
In your rebuttal you write (raws 410-411) that in Supplementary Text 2 there is a more detailed description of the selection, in addition to what is written in the main text. Unfortunately the supplementary Text 2 is unchanged compared to the original submission, it deals only with the samples reported in Barberi et al. (1975).
I have seen that in Supplementary Table 2 the sample list has been sorted differently than in the original file, separating, for each bibliographic reference, the data taken into consideration for Figs.2 and 3, from those not used. The only noteworthy change is related to two samples from Lahitte et al. (2003), 75B1 and 75D, which were not used in Figs. 2 and 3 of the original version (and are not used in the revised version). In the table is now explained why they were not used. I wonder why you focused on those two samples.

Dear Reviewers

We have incorporated all your suggestions (with one exception regarding the comment on Fig. 3) in the new manuscript version (Manuscript and Figures.pdf) and provide here a point-by-point response to your comments.

Note:

1) *All references to the manuscript lines of this file refer to the track changed version of the manuscript.*
2) *According to the reviewer suggestion and the journal guidelines the methods section has been moved to the end of the main text but without marking them with track change for sake of clarity.*
3) *The references in the manuscript were added using the Zotero plugin in Word, and tracking changes can become chaotic since modifications are not always properly recorded. Therefore, we did not use track changes for reference updates and have instead listed the added and removed references at the end of this file.*

Reviewer #1 (Remarks to the Author):

I would recommend acceptance of the work with moderate/minor reviews. Most of which is in the organization and topics covered in introduction, as well as opening to a more regional context in the discussion. My main comments are below and I also commented directly on the manuscript.

* What are the major claims of the paper?
This paper presents new research on the Afar Depression in Ethiopia, a region characterized by active continental rifting. The authors use new 40Ar-39Ar dating of volcanic rocks synthesize this data with existing geochronological and geochemical information to reconstruct the temporal and spatial evolution of the rift, focusing on the Stratoid series, a large suite of volcanic rocks erupted between 4.5 and 0.88 million years ago. They find that the rift experienced a process of asymmetric localisation, narrowing progressively from a wider zone of extension to a more focused magmatic segment, while also migrating northward. This localization, the researchers argue, is driven primarily by plate motion rather than a deep mantle plume. The researchers also observe a geochemical signature suggesting that the magmatic system became shallower and more complex during localization, consistent with thinning of the lithosphere and the formation of shallow magma chambers.

* Are these claims novel, and will they be of interest to others in the community? If the conclusions are not original, it would be helpful if you could provide relevant references.
This comprehensive dataset allows them to propose a model for rift evolution and volcanic activity that challenges previous interpretations. Indeed, they propose that this rift localization, rather than being driven by a mantle plume, is primarily caused by the divergent motion of the Arabian and Nubian plates. Moreover, this work provides one of the most precise spatio-temporal constraints on rift localization. Overall, this study provides new insights into the dynamics of continental rifting and the role of tectonic forces versus mantle plumes in shaping the volcanic landscape. Even if these claims are not novels (e.g. Rychert et al 2012), the topic is controversial, and they bring new petrographic, geochemical and chronological evidence which will be of great interest to the community.

* Is the work convincing, and if not, what further evidence would be required to strengthen the conclusions?
I'm not a geochemist and I'm not able to judge the pertinence and quality of the data. However, the method used is very standard and I don't see any odd or incoherent age when compared to available

data in the bibliography. Moreover, the method is carefully explained and all the raw data is made available for anyone who wishes to reproduce and check the results.

* On a more subjective note, do you feel that the paper will influence thinking in the field in terms of either conceptual understanding or technological capability? Please feel free to raise any further questions and concerns about the paper.

I find this paper interesting as it provides new and qualitative data on AFAR volcanism. Moreover it provides great insight in rift localization and rift evolution in this complex area. I would however point out that it lacks the regional context, which I think should be developed in the introduction with appropriate references (i.e. the work of Wolfenden is cited in introduction for Arabia-Nubia separation when it focuses only on Nubia-Somalia separation). In that regard, I think a more thorough and precise, yet brief paragraph on the regional geology is needed in the introduction. It would allow to discuss the implications of the evolution of rift localization and timing in regards to the complex Red Sea-Aden-EARS triple junction.

Reply: We thank the reviewer for pointing that out and have now reorganized and improved this paragraph (line 60-69) of the introduction by I) inserting the correct references for the Arabia-Nubia motion (i.e., Wolfenden et al., 2005 and Watchorn et al., 1998 for the beginning of the rifting and ArRajehi et al., 2010 and Reilinger and McClusky, 2011 for the constant rate of rifting since 11 Ma ; respectively line 62 and line 64) and for Somalia-Nubia motion (i.e., Wolfenden et al., 2004 and Stamps et al., 2008; line 68) extension; II) expanding on regional context of the Afar triple junction formation and evolution, giving the reader a broader view of the configuration and evolution of the Afar rift branches (line 64-69). Accordingly, we also added a brief paragraph in the discussion where we framed our study in the Afar context (particularly referring to the Arabia-Nubia divergent motion) to support the linkage of the Gulf of Aden-Red Sea system taking place in Central Afar and the distinction between the Red Sea and the Afar Rift (line 280-286).

The authors could also have a look at the paper by De Chabalier and Avouac (1995: Kinematics of the Asal rift (Djibouti) determined from the deformation of Fieale Volcano), where they suggest that decompression melting due to lithospheric thinning dominates the processes, and discuss how does this differ from the Tendaho-Dabbahu Manda Hararo segment?

Reply: We thank the reviewer for pointing out this paper. We added reference to this work to the manuscript (line 279) as evidence of partial melting being induced by adiabatic *decompression in support of our interpretation of Arabia and Nubia divergent motion driving rift localization.*

I would also consider discussing the results in regard of the (very) new paper of Ben Mather (Spreading ridge migration enabled by plume-ridge de-anchoring, Nature Communications),

Reply: We thank the reviewer for pointing out this paper. We have incorporated it into the manuscript (line 276-278) and discussed it to support our interpretation that the divergent motion of Arabia and Nubia drives rift localization.

On a more formal note, I find the use of abbreviation excessive and exhausting, if in some cases justified, it should not be systematic

Reply: As suggested by the reviewer we replaced the abbreviations with their full name at the beginning of each chapter to reduce the number of acronyms and improve readability.

Reviewer Manuscript comments:

Line 40-41: rephrase

Reply: We have rephrased the sentence (line 47-49).

Line 42-43: locate, fig1b is too small and lacks clarity. Maybe the geology from Fig 1b could be displayed on Figure 1c in the background ? You might have to play with the colors of the samples. If it is not conclusive I would still suggest to modify Fig1b so that the names appear more clearly. All the names mentionned in text should appear on the figure.

Reply: According to the reviewer suggestion we have made Fig. 1 clearer by distinguishing the segments of the three rift branches in Fig. 1a and by merging Fig. 1b and 1c in the new Fig. 1b. As suggested by the reviewer we have inserted in the background of Fig. 1b the geology layer and, for sake of clarity, the name of all the key features have been inserted into a legend and referred to in the map by means of numbers.

Line 52-53: Wrong reference, this is about Nubia-Somalia. For Arabia-Nubia, separation started much earlier and with maximum rates at 16mm.yr (Chu and Gordon, 1998; Augustin et al., 2021;Delaunay et al., 2023;Baby et al.,2024).. As mentionned in my general comments, I would slightly reorganize the introduction with a small paragraph on the regional geology of this triple junction (Red Sea, Aden, EARS).

Line 82-85: a few sentences on arabia nubia separation would be helpful, see my previous comment.

Reply: We thank the reviewer for pointing that out and have reorganized and improved this paragraph (line 60-69) of the introduction by I) inserting the correct references for the

Arabia-Nubia motion (i.e., Wolfenden et al., 2005 and Watchorn et al., 1998 for the beginning of the rifting and ArRajehi et al., 2010 and Reilinger and McClusky, 2011 for the constant rate of rifting since 11 Ma ; respectively line 62and line 64) and for Somalia-Nubia motion (i.e., Wolfenden et al., 2004 and Stamps et al., 2008; line 68) extension; II) expanding on the regional context of the Afar triple junction formation and evolution, giving the reader a broader view of the configuration and evolution of the Afar rift branches (line 64-69). Accordingly, we also added a brief paragraph in the discussion where we framed our study in the Afar context (*particularly referring to the Arabia-Nubia divergent motion) to support the linkage of the Gulf of Aden-Red Sea system taking place in Central Afar and the distinction between the Red Sea and the Afar Rift (line 280-286).*

Line 184: I would recommend reformulating this paragraph, it is difficult to describe what you mean and I'm not sure I understand fully.

Reply: We thank the reviewer for pointing that out.
According to this and other comments of the reviewers, to help the reader understand the models described in this paragraph we: I) replaced the term "rift spreading" with "ocean spreading-like rifting" throughout the manuscript to prevent any ambiguity associated with the term "rift spreading"; II) defined in the introduction what we meant with the term "rift localisation" and "ocean spreading-like rifting" (line 97-101).
We have then improved the paragraph in question by I) stating that the extension rate of the models remains constant through time (line 155); II) better explaining how the volcanism is distributed during ocean spreading-like rifting and rift localisation in the theoretical models, in particular why rift localisation may lead to a greater rate of the volcanism younging toward the center of the rift with respect to a ocean spreading-like rifting scenario (line 164-169).

Line 186: reference?

Reply: We added Buck (1991) and Brun (1999) as references for the geometry and the transition between wide and narrow rifts (line 155).

Line 186: harmonize spelling with figures

Reply: We corrected the spelling in Fig. 2

Line 198-199: yet similar, in the error margin

Reply: The reviewer is correct, we have added "comparable but still slightly higher" to underline the two values are similar (line 160-161).

Line 249: See my general comments. I would try to connect more your observations and results with the regional context

Reply: We thank the reviewer for pointing that out and added a brief paragraph in the discussion where we framed our study in the Afar context (particularly referring to the Arabia-Nubia divergent motion) to support the linkage of the Gulf of Aden-Red Sea system taking place in Central Afar and the distinction between the Red Sea and the Afar Rift (line 280-286).

Line 273-274: What would therefore be the role of the AFAR plume ? Would there still be volcanism if there was no plume at all ? (genuine questions).

Reply: We thank the reviewer for the interesting question. We think that both mantle plume and rifting are required to produce the studied Afar volcanism. The presence of a mantle plume is ubiquitous beneath the whole of northern East Africa (e.g. Civiero et al., 2016), causing the mantle potential temperature of the asthenosphere to be ~100 °C higher than the unperturbed mantle (Ferguson et al., 2013; Rooney et al., 2012; Feyissa et al., 2019). Considering the Afar lithosphere thickness (~60-80 km; e.g. Lavayssiere et al., 2019; Ferguson et al., 2013) the elevated mantle temperature (and therefore the Afar plume) is necessary to induce partial melting below this depth range (Ferguson et al., 2013). However, petrological models show that a plume alone would also not cause significant mantle melting since without extension, the lithosphere would not be sufficiently thinned for melt generation (McKenzie and Bickle, 1988). We therefore interpret the plume to be a ubiquitous feature of the Afar region, influencing the overall melt volumes, but with the rifting above it being the primary control on the locus of magmatism. We better explained our vision on the role of the mantle plume in the manuscript (line 253-263).

Line 286-287: I find this really interesting but I think the authors should expend on this idea, putting their work in perspective of the regional tectonics.

Reply: We thank the reviewer for pointing that out and added a brief paragraph in the discussion where we framed our study into the Afar regional context (particularly referring to the Arabia-Nubia divergent motion) to support the linkage of the Gulf of Aden-Red Sea system taking place in Central Afar and the distinction between the Red Sea and the Afar Rift (line 280-286).

Line 331: Would it be possible to put the geology layer on Fig1c ? even with significant transparency, just as a reference ? On Fig1b, make sure all the names mentionned in text are there, and try to make the names appear more clearly.

Reply: According to the reviewer suggestion we have made Fig. 1 clearer by distinguishing the segments of the three rift branches in Fig. 1a and by merging Fig. 1b and 1c in the new Fig. 1b. As suggested by the reviewer we inserted in the background of Fig. 1b the geology layer and, for sake of clarity, the name of all the key features have been inserted in a legend and referred to in the map by means of numbers.

Line 367: maybe add a small inset map to show again where this profile is located ? I find this figure a bit lonely. It is clear thu.

Reply: We agree with the reviewer that the figure may appear somewhat isolated. However, we chose not to include the profile map to avoid redundancy with the existing topographic profile and have kept Fig. 3 as a single-column figure.

Reviewer #2 (Remarks to the Author):

Dear Editor,

In their contribution entitled New 40Ar-39Ar dating of the Afar Stratoid series shows progressive rift localisation in Afar (Ethiopia), Tortelli et al. use the distribution, ages and geochemistry of extrusive lava series in the region of Afar to deduce that (1) extension is accommodated by rift localization rather than steady-state magmatic accretion; and (2) the melting source of magma is becoming shallower with time. Based on these conclusions, they assert that the magmatic activity observed in the Afar region is unlikely to be related to a plume and suggest that it is rather linked to the extensional plate tectonic settings.

First, I must state that I am neither a specialist of thermochronological methods, nor of the Afar study area, and hence I have not judged these aspects of the manuscript. This said, I found the data and their interpretation presented in the study convincing. This study is of interest for a broad range of earth scientists. Questions related to the importance of plumes in magma-rich rift systems are timely, and the new data and more importantly the new look provided by this study to feed this heated debate are welcome. The figures are relevant, clear and readable. The manuscript is well referenced and includes recent studies.

My main concern about this contribution relates to the clarity of the used terminology and concepts. Some terms are not of common use (e.g., “rift spreading”), and yet they are not defined.

Reply: We thank the reviewer for pointing that out and according to this and other comments of the reviewer we replaced the term “rift spreading” with “ocean spreading-like rifting” throughout the manuscript to prevent any ambiguity associated with the term "rift spreading”. We also clarified what we meant with the terms “ocean spreading-like rifting” *(i.e., the width of the extension zone do not change through time and the volcanism gets progressively younger toward the rift centre at the same rate as rift extension) and "rift localisation" (i.e., the magmatism youngs toward the rift centre at a faster rate than rift extension due to the width accommodating the extension progressively narrowing through time) in the introduction (line 97-101).*

Other definitions are awkward (e.g. "Asymmetry in rates but with the total still equal to the full spreading rate implies asymmetric spreading").

Reply: We have now provided a more concise and clear statement (i.e., "Unequal rates between rift sides yet yielding the full extension rate, implies asymmetric ocean spreading-like rifting"; line 160-161 and 170)

A definition of what the author mean with "crust" would also be welcome: is it fully continental (pre-rift) crust? Fully newly created magmatic crust? Partially continental and partially magmatic crust?

Reply: This is an interesting question, as the topic is still debated. The crust in Afar is neither entirely continental nor entirely oceanic, instead, it is often described as transitional between the two (e.g., Hammond et al., 2011). We added a brief explanation of the nature of the crust in the manuscript (line 70-72).

This contribution would also benefit from a clearer and more concise presentation of the scientific question guiding this study, and a better highlight of its results in the Abstract and/or Introduction sections.

Reply: We have now I) clearly pointed out the scientific questions addressed in this work both in the abstract and in the introduction (line 19-24 and line 43-44); II) improved the presentation of our results by defining key terminology (i.e., ocean spreading-like rifting and rift localisation) and explicitly ruled out the ocean spreading-like style of rifting for the studied volcanism, both in the abstract and in the introduction (line 27-28 and line 97-101).

Please find below my detailed comments:

Abstract

Line 20: why mentioning the Wilson Cycle? It is not relevant to this study.

Reply: According to the reviewer comment we reformulate the beginning of the abstract to better present the scientific question of the study.

Line 24-25: the term "in-rift localisation" is very uncommon, it merits to be defined.

Reply: We defined what we meant with rift localisation at line 26-27.

Line 27-28: “changes in the spatio-temporal distribution of volcanism and erupted lava volumes during rift localisation can be induced by plate motions”. Awkward statement, consider rewording.

Reply: We reworded the sentence (line 30-34).

Isn’t the conclusion that Afar shows rift localization rather than magmatic accretion a result of this study? If so, it merits to be presented as such in the abstract.

Reply: We added a statement to explicitly rule out an ocean spreading-like style of rifting for the studied volcanic activity (line 27-28).

Introduction:

Line 32: “rifting and break-up is commonly associated with a mantle plume” I suggest tempering this statement since recent studies tend to support the converse is true (e.g. Sauter et al., 2023; Scientific Reports; 13:1195; https://doi.org/10.1038/s41598-023-28364-y)

Reply: We replaced “commonly” with “can” (line 38)

Line 42: “Dalha” is labelled “Daha” in Fig. 1.

Reply: Dalha is spelled correctly in Fig. 1. Is it the reviewer referring to some other figure?

Line 47: “the main graben faults” are not labelled in fig. 1

Reply: Yes, the main graben faults are not mapped to avoid making the image too chaotic. We removed the reference to “Fig. 1” to prevent any misinterpretation that these faults are explicitly mapped in the figure (line 55).

Line 52: when extension is still going on in this direction replace “has occurred” by "has been occurring"

Reply: We reformulated the phrase (line 60-63).

Line 53: “The crust is generally around 25-30 km thick”. Do you mean fully continental crust, fully magmatic crust, partially continental and magmatic or crust of unknown origin?

Reply: This is an interesting question, as the topic is still debated. The crust in Afar is neither entirely continental nor entirely oceanic, instead, it is often described as transitional between the two (e.g., Hammond et al., 2011). We added a brief explanation of the nature of the crust in the manuscript (line 70-72).

Line 54-55 you write “Extension in Afar started 55 at ~29-25 Ma” and then at Line 56 “Starting at ~4.5 Ma, extension has instead…” please clarify.

Reply: What we meant is that extension in Afar started at ~29-25 Ma and it was first associated with the development of rift margins and marginal basins (~20-4.5 Ma) and then, starting at 4.5 Ma, has been loosely associated with the Stratoid. We clarified this concept in the manuscript (line 72-76).

Line 63: "Stab et al. interpret…" please add the publication year.

Reply: If I correctly understood the formatting guide the publication year has not to be inserted.

Line 66-67: "a spreading centre-like scenario". Please clarify: do you mean that continental extension if fully accommodated by magmatic accretion?

Reply: Yes, we clarified here (line 85-86) that with "spreading centre-like scenario" we meant that nearly all the extension is accommodated through magmatic accretion.

Line 77-78: "rift localisation and rift spreading": please clarify what you mean with both terms.

Reply: We thank the reviewer for pointing that out and according to this and other comments of the reviewer we replaced the term "rift spreading" with "ocean spreading-like rifting" throughout the manuscript to prevent any ambiguity associated with the term "rift spreading". We also clarified what we meant with the terms "ocean spreading-like rifting" (i.e., the width of the extension zone do not change through time and the volcanism gets progressively younger toward the rift centre at the same rate as rift extension) and "rift localisation" (i.e., the magmatism youngs toward the rift centre at a faster rate than rift extension due to the width accommodating the extension progressively narrowing through time) in the introduction (line 97-101).

Results:

Line 158: what does "m.a.s.l." stand for?

Reply: m.a.s.l. stand for meter above sea level. We replaced it the abbreviation form of "metre" (line 117)

Line 184-194: This paragraph presents a key point of your interpretation, and hence it would merit to be clarified. Why does rift localization imply a greater extension rate compared to magmatic spreading? When you refer to spreading, do you imply steady-state/constant rate magma accretion or can the accretion rate vary with time?

Reply: We thank the reviewer for pointing that out.

According to this and other comments of the reviewers, to help the reader understand the models described in this paragraph we: I) replaced the term "rift spreading" with "ocean *spreading-like rifting" throughout the manuscript to prevent any ambiguity associated with the term "rift spreading"; II) defined in the introduction what we meant with the term "rift localisation" and "ocean spreading-like rifting" (line 97-101).*

We have then improved the paragraph in question by I) stating that the extension rate of the models remains constant through time (line 155); II) better explaining how the volcanism is distributed during ocean spreading-like rifting and rift localisation in the theoretical models, in particular why rift localisation may leads to a greater rate of the volcanism younging toward the center of the rift with respect to a ocean spreading-like rifting scenario (line 164-169).

Figures:

Fig. 1: I suggest increasing the size of panel b compared to panel c since there is much more to read in the former compared to the latter.

Reply: According to the reviewer comments we made Fig. 1 clearer by distinguishing the segments of the three rift branches in Fig. 1a and by merging Fig. 1b and 1c in the new Fig. 1b. We inserted the geology layer in the background of Fig. 1b and, for sake of clarity, the name of all the key features have been inserted in a legend and referred to in the map by means of number.

Fig. 2: in panel c, you may want to specify that the different colored boxes represent the extended area during a given time period.

Reply: We made clearer in the caption that the coloured boxes indicate the areas accommodating the extension during a given time period.

Reviewer #3 (Remarks to the Author):

I would like to point out that I am a geochronologist, not an expert in structural geology. Therefore, I will focus on the geochronological part, which is anyway the basic scheme for all other considerations. This paper is an original contribution to the study of the Afar region, based on a fair number of new age data and a far greater number of literature data. The latter are the weak point of the article, as I will discuss later. The new 40Ar39Ar analyses expand the number of ages obtained with this method in the area, not many as highlighted by supplementary Table 2, where conventional and unspiked K/Ar data are prevalent. Duplicate 40Ar39Ar analyses of several samples show on average good reproducibility, with rare exceptions (sample AF20-60b maybe deserves more attention). I find questionable the choice not to use both results of the analyses performed in duplicate. Moreover, on average the errors of the two replicate analyses differ little in percentage terms. The average of the two measurements, having Authors discarded the combination of plateau steps (rows 147÷150), seems to me more appropriate and consistent with the analyses performed. However, the chosen criterion is irrelevant in the regional context in which these ages are used, it could be in other geochronological contexts.

Reply: We agree with the reviewer that the criteria chosen to present the data measurement need a careful evaluation for certain geochronological contexts, however, we are glad the reviewer recognizes that the choices made regarding data section would have little impact on changing the overall interpretations we make, mainly due to the large spatial scale nature of the problem we are solving.

Three out of 16 samples show a consistent difference among isochron ages (with an initial 40Ar/36Ar ratio slightly radiogenic) and total integrated age (equivalent to a K/Ar age), the last one is definitely older. Unless this difference is attributed to recoil problems, a hypothesis discarded in the text (rows 21÷24, Supplementary text 1), a doubt arises about the literature K/Ar data used in the model resented by the Authors. By the way, Authors are the first to mention the greater reliability of 40Ar39Ar technique compared to K/Ar one (Supplementary Text 2) and to discard some literature K/Ar data because newly obtained 40Ar39Ar are younger. K/Ar ages assume an initial atmospheric 40Ar/36Ar ratio, and this is not always true as some analyses in this article also demonstrate. Now K/Ar ages represent more than 50% of the data used in Fig. 2 and 3 for the model.

Reply: We thank the reviewer for pointing that out and we understand the concern about the literature data. However, despite the excess of 40Ar/36Ar observed in some Afar samples, most of our analysis have coherent isochron ages and integrated age and are overall concordant with literature age ranges of the studied series (as shown in the "40Ar-39Ar geochronology" section). Furthermore, where our samples are collected at very close location to the literature samples, they show similar ages (e.g., sample 75D of Lahitte et al., 2003 and AF20-69(A) of this work having respectively 1.89 ± 0.058 and 1.92 ± 0.012 Ma or sample GB23 of Kidane et al. (2003) and our samples Z4 having respectively and age of 2.02 ± 0.04 and 2.02 ± 0.02 Ma). We therefore suggest that even if some problems can arise from literature data (as we pointed out for Barberi et al. (1975) samples) overall the literature dataset is concordant with our analysis and therefore suitable for the typology of geochronological study carried out in this work.

There is a discrepancy (or I misunderstood) in chapter 40Ar39Ar geochronology between the first two rows and the last two rows. You indicate an age range for each of the three series, LS, US and Gu, apparently valid for the entire area according to your sampling criteria. Your new ages highlighted a narrow age gap between LS and US, and a more consistent gap between US and Gu. At the end of the chapter you claim that the volcanic activity was continuous and without overlap among series. If you really sampled the bottom and the top of the series, there are gaps in volcanic activity, and there are problems with several literature K/Ar data. If the mentioned intervals of activities refer only to samples dated in this article, then literature data taken as a whole (Supplementary Table 2) show overlap among series, only the dataset used for figure 2 and 3 don't show overlaps. Please clarify.

Reply: We thank the reviewers for pointing that out. The reviewer is correct, there are differences between our analysis age ranges in the first two rows (showing gaps) and the whole dataset age ranges in the last two rows (no gap). However, we do not think this discrepancy is necessarily related to problems with literature data but can have a geological explanation. Our sampling area is smaller and differs from that of the literature dataset and, given the conclusion of this study (i.e., the rift/volcanism moved in space and time), it is possible the even if we sampled the top of a series (e.g., the uppermost US sample we dated at 2.02 Ma), that series may have ceased erupting at our sampling location while continuing elsewhere (as indicated by younger US samples, both in published and new data).
We clarified in the manuscript that the last rows refer to our new analysis and published data together (line 121-122). In other words, due to spatial variability in the locus of volcanism, there are gaps between series on localised spatial scales, but no gaps over the complete regional scale of Afar..

Is the selection criterion for the samples in rows 180-181 the only one used? I suggest explaining in much more detail than reported in the text the selection criteria of literature samples used in figures 2 and 3, if there are at least some stratigraphic constraints on chosen samples, and if there are samples excluded because considered unreliable. In other words, a critical evaluation of the literature data is necessary for the use that has been made of them in the article.

Reply: We thank the reviewers for pointing that out and have now explained the criteria we used to select literature samples in the main text (line 137-145) and appropriately referenced the Supplementary Text 2 where a more detailed description of the selection is presented.

The last remark is formal: if I have interpreted the rules of the magazine correctly, methods should be inserted at the bottom of the main text.

Reply: We thank the reviewers for pointing that out and we moved the methods at the end of the main text (we do not used track change for this modification).

Manuscript references updates:

Removed:

DeMets, C. & Merkouriev, S. High-resolution estimates of Nubia–Somalia plate motion since 20 Ma from reconstructions of the Southwest Indian Ridge, Red Sea and Gulf of Aden. Geophys. J. Int. 207, 317–332 (2016).

Added:

ArRajehi, A. et al. Geodetic constraints on present-day motion of the Arabian Plate: Implications for Red Sea and Gulf of Aden rifting. Tectonics 29, 2009TC002482 (2010).

Barberi, F., Ferrara, G., Santacroce, R. & Varet, J. Structural evolution of the Afar Triple Junction. in (STUTTGART, 1975).

Brun, J. P. Narrow rifts versus wide rifts: inferences for the mechanics of rifting from laboratory experiments. Philos. Trans. R. Soc. Lond. Ser. Math. Phys. Eng. Sci. 357, 695–712 (1999).

Buck, W. R. Modes of continental lithospheric extension. J. Geophys. Res. Solid Earth 96, 20161–20178 (1991).

De Chabalier, J.-B. & Avouac, J.-P. Kinematics of the Asal Rift (Djibouti) Determined from the Deformation of Fieale Volcano. Science 265, 1677–1681 (1994).

Eagles, G., Gloaguen, R. & Ebinger, C. Kinematics of the danakil microplate. Earth Planet. Sci. Lett. 203, 607–620 (2002).

Civiero, C. et al. Small-scale thermal upwellings under the northern east african rift from S travel time tomography. J. Geophys. Res. Solid Earth 121, 7395–7408 (2016).

Mather, B. et al. Spreading ridge migration enabled by plume-ridge de-anchoring. Nat. Commun. 15, 8934 (2024).

McKenzie, D. & Bickle, M. J. The volume and composition of melt generated by extension of the lithosphere. J. Petrol. 29, 625–679 (1988).

Moucha, R. & Forte, A. M. Changes in african topography driven by mantle convection. Nat. Geosci. 4, 707–712 (2011).

Reilinger, R. & McClusky, S. Nubia–Arabia–Eurasia plate motions and the dynamics of Mediterranean and Middle East tectonics. Geophys. J. Int. 186, 971–979 (2011).

Stamps, D. S. et al. A kinematic model for the East African Rift. Geophys. Res. Lett. 35, (2008).

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

Wolfenden, E., Ebinger, C., Yirgu, G., Deino, A. & Ayalew, D. Evolution of the northern Main Ethiopian rift: birth of a triple junction. Earth Planet. Sci. Lett. 224, 213–228 (2004).

Reviewer #3 (Remarks to the Author):

I acknowledge the replies to my review and changes made in the text. I have just a couple of brief notes.

In your rebuttal you write (raws 410-411) that in Supplementary Text 2 there is a more detailed description of the selection, in addition to what is written in the main text. Unfortunately the supplementary Text 2 is unchanged compared to the original submission, it deals only with the samples reported in Barberi et al. (1975).

> Reply: We recognize that our previous reply might have been unclear. As stated by the reviewer the Supplementary Text 2 is indeed unchanged with respect to the original version, and this is because it aims to explain only why we exclude the samples of Barberi et al. (1975), as it was in in the original version. The remaining exclusion criteria (i.e., the selection of samples only from the uppermost flows) is explained in the main text (lines 133–138) and the supplementary Data 1 and 2 provide the name of the excluded samples.

I have seen that in Supplementary Table 2 the sample list has been sorted differently than in the original file, separating, for each bibliographic reference, the data taken into consideration for Figs.2 and 3, from those not used. The only noteworthy change is related to two samples from Lahitte et al. (2003), 75B1 and 75D, which were not used in Figs. 2 and 3 of the original version (and are not used in the revised version). In the table is now explained why they were not used. I wonder why you focused on those two samples.

> Reply: We focused on these two samples because they are the only ones in literature that have been explicitly identified as sampled from the lowermost flows of the escarpment. They were therefore excluded, together with our sample Z135, to avoid potential age variations related to differences in stratigraphic height.

New ^{40}Ar-^{39}Ar dating of the Afar Stratoid series shows progressive rift localisation in Afar (Ethiopia)

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Abstract

During rifting the lithosphere gets thinner through stretching and heating until continental break-up occurs and oceanic crust starts forming. Rift evolution is a fundamental aspect of the Wilson Cycle and of particular interest is how and when the localised, mid-ocean ridge-like magmatism forms. Here we present new ^{40}Ar-^{39}Ar dating of 16 lava flows sampling the volcanism induced by rifting in Afar. Together with literature data, we reconstruct the spatio-temporal evolution of the rift from widely distributed to localised magmatic segments. We show that over 2-2.5 Myrs, the rift progressively narrowed by asymmetric in-rift localisation and also propagated along-rift. Concurrently, the mantle partial melting and the crustal magmatic system shallowed. We conclude that focused magmatic segments can form in a relatively rapid time period and that changes in the spatio-temporal distribution of volcanism and erupted lava volumes during rift localisation can be induced by plate motions without a significant role played by a mantle plume.

Introduction

Magma-rich continental rifts are characterised by large volumes of intruded and erupted igneous rock[1,2], in part because rifting and break-up is commonly associated with a mantle plume[3,4,5]. Since mantle melting can result from plume related thermal anomalies and mantle flow[6,7,8,9], as well as rift related decompression melting beneath thinning lithosphere[10,11,12], the evolution of magmatism in space and time is typically complex[13,14]. Specifically, it has proven challenging to identify when and how highly localised magma intrusion and coupled volcanic systems, typical of the mid-ocean ridge plate boundaries form during rifting.

In this regard, the Afar depression represents a unique place to study the spatial and temporal evolution of magmatism during rift evolution. Rifting in Afar initiated in the Oligocene, toward the end of the Ethiopian-Yemen Flood Basalt volcanism (~31-29 Ma[15,16]), and within the depression the magmatic record of the rift evolution up to the ongoing activity is currently exposed (Fig. 1). The older rift products are the 20-10 Ma silicic Mabla series and 10-4 Ma mainly mafic Dalha and Dalhoid series, outcropping only at the Afar margins[17]. The central areas of the depression are instead dominated by the widespread Stratoid series (Fig. 1), consisting of sequences of mostly mafic lava flows reaching 1 km in thickness. In particular, South Afar is dominated by the Lower Stratoid series (LS; 4.5 - 2.57 Ma[18]) while Central Afar by the Upper Stratoid series (US; 2.87 - 0.88 Ma[18,19]). In Central Afar the US were followed by the mostly mafic Gulf series (Gu; 1.11 - 0.32 Ma[20,21]), which erupted principally along the main graben faults[22] (Fig. 1) and marked a decrease in volume with respect to the US[17]. Broadly at the same time, several silicic central volcanoes formed throughout Afar (CV; ~2 - 0.5 Ma[23,24]). The ongoing, localised Axial series (Ax; <1.09 Ma[21]) show both mafic to silicic central volcanoes and mafic fissural eruptions (Fig. 1), the latter exemplified by the 2005-2010 rifting episode at the Dabbahu-Manda Hararo (DMH) magmatic segment.

Rifting between the Arabian and Nubian plates causes extension in Afar[25] and has occurred in a ~NE direction at 16-20 mm/yr since at least 8 Ma[26]. The crust is generally around 25-30 km thick, but locally thins to 15-20 km beneath the current magmatic segments such as the DMH[27,28]. Extension in Afar started at ~29-25 Ma, leading to the development of rift margins and marginal basins and followed by the eruption of the Mabla, Dalha and Dalhoid series[17,29,16]. Starting at ~4.5 Ma, extension has instead been loosely interpreted to be associated with the eruption of the Stratoid series within the depression[29]. The Stratoid series has been described as a pulse of volcanism migrating to the north[20], broadly associated with the transition from continental rifting to break-up[23,30], or to the first stage of oceanization[31]. There are clear age[22] and petrological[32] variations between the LS and US, which have been linked to different extensional events[17], most likely related to a sudden shift (or jump) of extension from South to Central Afar[27,32]. Within the US, however, there is significant debate regarding their temporal and spatial distribution and link to rift evolution. For example, Stab et al. interpret the broad US spatial distribution to be associated with equally broad extension in Central Afar[29], only followed by rift localisation with the onset of the Gu at 1.1 Ma[20]. In contrast, other authors have recognised younging of the Stratoid toward the centre of the Tendaho graben[30] and magnetic stripes akin to classic mid-ocean ridge patterns[33], implying a spreading centre-like scenario. At the same time, a progressive northward migration of the Stratoid spreading axis has been suggested based on the ages of the Central Afar silicic activity[31]. In addition to a tectonic control leading to decompression melting[33,11,12], a number of studies have suggested that the Afar plume[34] controls the volcanic activity and rift evolution[35,36,37,38,39,40]. As such, the spatial and temporal distribution of the US and how it relates to the rifting process is still unclear. The lack of a detailed tectonic framework has also hindered the interpretation of controls on the geochemistry of the US, such as evolution of the mantle source and subvolcanic plumbing system. Therefore, the mechanisms controlling the spatio-temporal evolution of magmatic activity during rifting in Afar remain poorly resolved[41].

To address these issues, we provide new ^{40}Ar-^{39}Ar data for 16 LS, US and Gu lava samples from South and Central Afar. We reconstructed the distribution in space and time of the volcanic activity during rifting in Afar. By comparing our observations with models of magma distribution during rift localisation and rift spreading, we identified an asymmetric localisation of the rift in Central Afar. From an initially wide area accommodating diffuse extension (hereafter referred as Plate Boundary Zone; PBZ) (i.e., US eruption), the rift became progressively narrower and moved laterally to the current DMH magmatic segment position over the last 2-2.5 Myrs. Using geochemical and petrological literature data we identify a thinned lithosphere associated with a shallower and complex magmatic system for the localised phase. Finally, by combining our reconstruction with chemical data, we suggest that the spatio-temporal distribution of the volcanic activity during rifting is mainly driven by the divergent motion of Arabia and Nubia rather than being plume controlled.

Methods

Sampling

Sixteen lava flow samples (4 LS, 9 US and 3 Gu; Fig. 1) from a sampling campaign in 2020 and the Afar Repository of University of Pisa were selected based on their petrographic and geochemical analysis[32,42] in order to avoid any evidence of alteration. The selection of samples aimed to cover as much of South and Central Afar as possible, and to temporally constrain the eruptive period of the LS and US lava flows by dating the visible lowermost flows of the Dulul and Tendaho graben escarpments. The ^{40}Ar-^{39}Ar dating was carried out on the groundmass for all samples and on plagioclase phenocrysts for the silicic sample (AF20-69a; Supplementary Tab. 1). Samples preparation and analyses were carried out at the NEIF Argon Isotope Laboratory at the Scottish Universities Environmental Research Centre (SUERC).

Sample preparation

Initially, heavily weathered outer portions of each sample were removed using a Controls 32-D0536/A saw and the relatively fresh interiors were screened using a petrographic microscope to identify any signs of alteration in the groundmass and to evaluate the feasibility of analysis. Suitable whole rock samples were then crushed in a Pulverisette 1 jaw crusher producing fragments ~1-5 mm which were then fed into a Pulverisette 13 disc mill to further reduce the size before finally being sieved to produce a 250-500 µm separate. A hand magnet was used to remove any metal particles left over from the crushing process, before being rinsed in deionized water to remove any adhering dust and other loose fragments. The separates were then leached in an ultrasonic bath, for 20-30 minutes in a 2.5M HNO_3 solution to remove alteration phases which is then followed by a 3M HCl solution to remove olivine phenocrysts. These leaching steps are repeated as many times as is necessary to remove the unwanted materials. The samples were then cleaned in deionized water to remove dust, dried at temperature <75°C and sieved to remove possible fragments created by comminution during leaching. By repeated passage in a Frantz Isodynamic Magnetic Barrier Separator, non-magnetic phenocrysts and alteration products were separated from the magnetic lava groundmass, and feldspar phenocrysts were separated from the lava groundmass. Lastly, each lava sample has had ~400 mg of homogenous and unaltered groundmass hand-picked under a binocular microscope. For the feldspar separates, once obtained, they were further processed with the Frantz to isolate any remaining melt inclusion-rich feldspar grains and magnetic groundmass from the non-magnetic, melt inclusion-free, feldspar grains. The selected feldspar grains were then further leached in a 1M HF solution for 3-5 minutes to remove adhering glass, cleaned in deionized water and dried at temperature <75°C. The last step was to ensure all the feldspar grains were inclusion-free by hand-picking under a binocular microscope.

Sample analysis

Lava groundmass and feldspar samples and neutron flux monitors were packaged into 7-pit Al discs, sealed and then stacked in quartz tubes with the relative positions of packets precisely measured for later reconstruction of neutron flux gradients. The sample package was irradiated in the Oregon State University Triga reactor's Cadmium Lined In-Core Irradiation Tube (CLICIT) facility. The international ^{40}Ar-^{39}Ar standard, Alder Creek sanidine, 1.1891 ± 0.0008 Ma (± 1σ[43]) was used to monitor ^{39}Ar production and establish neutron flux values (J) for the samples. Gas was extracted from samples in a step-wise fashion, heated using a Teledyne-Cetac Fusions mid-infrared (10.6 µm) CO_2 laser with a non-gaussian, uniform energy profile and a 3.5 mm beam diameter. The samples were housed in a doubly pumped ZnS window laser cell and loaded into a copper planchette containing four 2.6 cm^2 square wells. Liberated argon was purified of active gases, (e.g., CO_2, H_2O, H_2, N_2, CH_4) using three Zr-Al getters; one at 18°C and two at 400°C. Data were collected on a Thermo Scientific ARGUS VI multi-collector mass spectrometer in static collection (non-peak hopping) mode. Time-intensity data are regressed to t_0 with second-order polynomial fits to the data. Blank corrections employed the average value and standard deviation of multiple blanks bracketing and interspersed with sample and air standard runs. Mass discrimination was monitored daily, both between and within sample runs, by comparison to running-average values of an air standard. All data are blank, interference and mass discrimination corrected using the MassSpec software package (MassSpec, authored by Al Deino, Berkeley Geochronology Centre, Version 8.149). Decay constants and corrections (Supplementary Table 1) were selected after Renne et al.[44].

Most of the samples were run in duplicate and a plateau age calculated for each analysis. Age and uncertainty were calculated using the mean weighted by the inverse variance of each step. The isochrons were calculated using the plateau steps to determine the composition of the trapped component and isochron age. The plateau age was accepted if I) it consists of at least five consecutive age steps indistinguishable within 2σ uncertainty, II) it comprises a minimum of 60% of the total ^{39}Ar released, III) it is concordant with the isochron age at the 2σ level, and IV) has a ^{40}Ar-^{36}Ar trapped component indistinguishable from air (298.56 ± 0.62) at the 2σ level (Supplementary Tab. 1). A number of analyses show small excess of ^{40}Ar*, i.e., a non-atmospheric trapped component. In these instances, the isochron age is preferred as the best estimate of the timing of emplacement and may be interpreted as a maximum age (see Supplementary Text 1 for detail). The replicated plateau ages overlap in age at the 2σ level. However, in many cases, combining plateau steps from replicates to calculate a composite plateau generated excess scatter such that MSWD exceeded the critical value at a given N. It is for this reason that we choose the most precise determination in a set of replicated analyses that satisfy the plateau acceptance criteria above as the best estimate of emplacement age. All the data are provided in Supplementary Tab. 1 and Supplementary Fig. 1. All ages are presented herein at 2σ uncertainty level.

Results

^{40}Ar-^{39}Ar geochronology

Our ^{40}Ar-^{39}Ar dating indicates that the LS ranges from 4.85 ± 0.06 to 2.89 ± 0.03 Ma, the US from 2.58 ± 0.04 to 1.88 ± 0.02 Ma while the Gu spans from 1.07 ± 0.03 to 0.34 ± 0.13 Ma (Supplementary Tab. 1). Our analyses extend the upper limit of the known LS range[18] by ~350 ky. Our ages for the US are also broadly consistent with the literature (2.87 - 0.88 Ma; Supplementary Tab. 2), but with our new samples allowing us to redefine the age of the US activity near the Tendaho graben. Our ages of the uppermost (~1250 m.a.s.l.) and lowermost (~500 m.a.s.l.) flows of the Tendaho graben range from 2.58 ± 0.04 to 2.02 ± 0.02 Ma. These ages indicate the US activity south of Tendaho began earlier than previously thought (2.14 ± 0.06 Ma[22]; Supplementary Text 2) and ceased around 2 Ma despite continuing elsewhere until 1.18 ± 0.08 Ma[18]. The determined ages of Gu agree with the literature data (1.11 - 0.32 Ma; Supplementary Tab. 2) and, overall, the whole dataset indicates that the eruptive activity of the last 5 My in South and Central Afar was continuous, without a significant temporal gap or overlap between the series (Fig. 1).

Temporal evolution models

During rift evolution, the total area accommodating the extension can vary in space and strongly influence the architecture of the rift[45]. Weakness in the lithosphere due to pre-existing structures[45,46] or thermo-mechanical perturbations[47,48] (i.e., magma intrusions) can drive strain localisation, causing a decrease in the width of the deformed area accommodating the extension[49]. In contrast, in an ocean spreading-like scenario the area accommodating the extension remains the same through time.

Assuming that each lava sample was emplaced near their eruptive centres, the age variation of the lavas in space can be to a first order indicative of the area accommodating the extension (i.e., PBZ or magmatic segment) and therefore the temporal and spatial evolution of rifting can be evaluated (i.e., spreading or localisation). This approach has commonly been applied in other magma rich rifts such as Iceland[50,51], much of the mid-ocean ridge system[52] and other regions of the East African Rift[53,54]. To define how strain and volcanism evolved in Central Afar, we analysed the ages and spatial distributions of the US, Gu and Ax eruptive products in the Tendaho-DMH area (white box in Fig. 1) where a wide suite of dating information is now available (Supplementary Tab. 2). New and literature analyses were plotted onto two sections, respectively across (Fig. 1 A-A'; Fig. 2) and along-rift (Fig. 1 B-B'; Fig. 3), to evaluate the age-distribution of lava samples with respect to the DMH magmatic segment. To avoid age variations due to different stratigraphic height, we plotted only the ages of the US uppermost lava flows. Overall, the volcanic activity gets younger toward the centre of the graben[20,30] (Fig. 2a) and also toward the NW, where mainly the <1.1 Ma Gu and Ax outcrop (Fig. 1; Fig. 3).

Using the distribution of lava ages across the rift we evaluate the mechanisms responsible for riftward younging of the volcanic activity. To do this, we calculate the rate at which volcanism gets younger towards the rift centre and compare it with what is expected from rift spreading (Fig. 2b) and from rift localisation (Fig. 2c). In a uniform spreading scenario, the magmatic segment position and width remain constant through time, and it spreads away at half of the extension rate equally on both sides of the rift (Fig. 2b). The rate at which the age of volcanic lavas change away from both sides of the rift centre will therefore be the same and their sum equal to the extension rate. Asymmetry in rates but with the total still equal to the full spreading rate implies asymmetric spreading (Fig. 2b). However, if the rate is greater than that expected from uniform spreading, then localisation from initially broad to more localised volcanism is required (Fig. 2c). The magnitude of the rate depends on the initial width of volcanism and rate of localisation. In this scenario, asymmetry in rates implies asymmetric localisation (Fig. 2c).

The lavas on the NE side of the Tendaho-DMH area (pale blue crosses in Fig. 2a) have erupted progressively closer to the DMH magmatic segment during the last 2.5 My, at a rate of 26.7 ± 2.3 mm/yr, considerably faster than the half extension rate in Central Afar of ~10 mm/yr[25]. On the SW side of the Tendaho-DMH area (purple crosses in Fig. 2a) the rate is less with respect to the NE side, 11.5 ± 1.5 mm/yr, but still higher than the half extension rate of ~10 mm/yr. This pattern argues for a localisation of the magmatism that occurred asymmetrically, from NE to SW during the last ~2 Ma. Furthermore, boreholes within the Tendaho graben[55,56] drilled the young Ax and Gu activity on top of the US, further arguing against a spreading scenario. This east to west localisation indicates that, at least part of the US PBZ, had to be located east with respect to the DMH magmatic segment. Accordingly, the Moho depth estimates[27,28] (Supplementary Fig. 2) projected on the same across-rift profile show a thinning of the crust coherent with the younging of the volcanic activity (i.e., toward the centre of the Tendaho graben; Fig. 2a).

Concurrently, all the series plotted on the along-rift profile show younging of the erupted products toward the north during the last ~2 Ma (Fig. 3), indicating that the rift propagated north while localising in-rift. Accordingly, our US ages at the Tendaho graben (lowermost and uppermost flow, 2.58 - 2.02 Ma) are ~250 ky older with respect to the northern Dobi graben (intermediate and uppermost flow, 1.93 - 1.76 Ma[20]), indicating that the northward propagation was already occurring during the US activity. The propagation is also confirmed by boreholes TD-1 and TD-2 of the Tendaho graben[55,56] where the volcanic deposits are topped by 600/700 m of sedimentary succession while at the borehole TD-3 along the Manda Hararo segment, the volcanic deposits have been found overall continuously up to the surface. This suggests that the magmatic activity ceased at some point after the end of the US eruption south of Manda Hararo while continuing up to the present day along the magmatic segment itself.

Geochemistry

Changes in the mantle source and in the crustal magmatic system of Tendaho-DMH magmatic activity during rift localisation are investigated using the geochemical composition of both the dated samples (this work and literature data) and the entire suite of the Tendaho-DMH chemical analysis (Fig. 4; Supplementary Fig. 3; Supplementary Tab. 2).

Partial melting in the deeper, garnet-bearing portions of the mantle can be identified with respect to the upper, spinel-bearing portions using the highly compatible HREE in garnet[57] (i.e., Tb_N/Yb_N) for the mafic rocks (MgO > 4 wt %). Melting of a garnet-bearing lower crust or garnet and amphibole fractionation can also influence Tb_N/Yb_N. However, these processes can be excluded due to the low crustal thickness of Central Afar[27] and to the absence of garnet and amphibole in the series lavas[32,58,59]. The effect on Tb_N/Yb_N due to mantle source heterogeneity can also be ruled out considering the similarity of the trace elements patterns, all corresponding to magma type 3 of Rooney[17] (Supplementary Fig. 4). Changes in Tb_N/Yb_N are therefore related to changes in the depth of melting[32]. We relate the depth of melting to the lithospheric thinning and exclude the role of mantle potential temperature since no correlation is observed between temperature and Tb_N/Yb_N[18,7]. The three series show a clear distinction in the Tb_N/Yb_N for both the whole dataset and the group of dated samples only (Fig. 4a). The US ranges mainly at 1.7-1.9, the Gu at 1.6-1.7 and the Ax at 1.3-1.5, indicating a shallowing of the partial melting column, and therefore a thinning of the lithosphere, from the US to Gu to Ax.

The degree of magmatic evolution of the samples (i.e., MgO wt%) and the overall stationing depth of the magma of the three series have been used to reconstruct the changes of the magmatic system architecture during rifting. In order to focus on the variations of the fissural magmatic activity systems we did not take into consideration analyses of the central volcanoes (i.e., Dabbahu). A variation of the MgO content between the series is observed for both the whole dataset and the group of dated samples (Fig. 4b). The US have a unimodal distribution of moderately evolved lavas (4-6 MgO wt%) while the Gu are dominated by a slightly more mafic composition (5-7 MgO wt%) with respect to the US (Fig. 4b). The Ax have instead a clear bimodal distribution with mafic (8-9 MgO wt%) and moderately evolved (5-6 MgO wt%) lavas (Fig. 4b). Furthermore, these variations are associated with changes in the stationing depth. Along the magmatic segments, the Ax plumbing system is arranged in stacked sills and vertical dikes[60,61] from the Moho level[62,63] to the upper crust[64,65,66,67] (up to 2 km depth) while, US and Gu stationed mainly in the middle-lower crust[42] (10-18 km). These observations indicate a transition from a deep and overall stable magmatic system buffering the moderately differentiated US composition to a more complex one for the Ax, where magma can either reach and differentiate at shallower levels or more rapidly rise to the surface emplacing more primitive lavas.

Discussion

The spatio-temporal reconstruction of the volcanic activity carried out in this work indicates that, over the last 2-2.5 My, the rift in Central Afar asymmetrically localised in-rift (Fig. 2) while propagating toward the NW (Fig. 3), marking the progressive transition from the initially widespread US eruptions to the current narrow magmatic segment. This suggests that the rift localisation process was more protracted than previously thought and started well within the US period, rather than being limited to the most recent Gu and Ax periods. We therefore interpret that the US volcanism is strongly linked to rifting and tracks the progressive localisation process of the rift. Our reconstruction indicates that the US are associated with continental rifting[23,30] as their spatio-temporal distribution is not consistent with a spreading-like style of extension[68]. Furthermore, the US distributes in space and time coherently with the subsequent Gu and Ax activity, identifying a progressive localisation process and arguing for a similar mechanism controlling the evolution of the volcanic activity. We therefore suggest that, as for the more recent volcanic activity[53,67], the distribution of the US eruption is controlled by the divergent motion of Arabia and Nubia rather than by a major plume control.

The interpretation of rift focusing is fully consistent with geochemical evidence for progressive shallowing of the melting column interpreted as thinning of the lithosphere (Fig. 4a) together with the development of a complex magmatic system (Fig. 4b) forming shallow magma chambers[64,65,66] in a thinned crust[27,28] (Fig. 2a). The deeper partial melting and magma storage of the US with respect to the Gu and Ax suggests the US are associated with continental rifting, as these depths are not consistent with a spreading-like scenario[69,13]. During rifting, the effect of magmatism[70,71], stretching[72,73] and metasomatism[74,75] can weaken the lithosphere[14] while melt and volatiles rising from the mantle can weaken the crust[76,77], explaining the observed shallowing of partial melting and magma chambers[78]. We therefore suggest that, during continental rifting, at least part of the shallowing of partial melting occurs during the rift localisation with broadly simultaneous changes in the crustal structure.

The suggested minor role played by the Afar plume in controlling the spatial and temporal evolution of the US eruption is consistent with Afar mantle chemistry and mantle potential temperature. The US have indeed a mantle source very similar to the older LS, Dalhoid and Dalha series[17] and to the younger Gu and Ax series[17,79,18], with no variations of the Afar plume component[34] occurring during partial melting. Similarly, the mantle potential temperature remains similar for LS, US, Gu and Ax[7,18] indicating no thermal perturbation of the mantle source. We therefore suggest the US eruption is not related to an increase of the plume activity with respect to the more recent volcanic activity as variations in a rising plume would have led to marked variations in both mantle temperature and chemistry[80,81].

Our reconstruction agrees with analogue and numerical models of rift evolution showing alternating periods of rift propagation and localisation[82], narrowing of the volcanic activity[45,83] and progressively shallower depths of sill emplacement[83] while the rift matures. Geological and geophysical observations in Afar also corroborate our model, such as magmatic segments propagating NW[84,24,85,86], the Manda Hararo segment shifting westward[87], the presence of the young Ma' Alalta magmatic segment NW of DMH[88] and the deeper melting column in the earlier stage of the rift[12]. The divergent motion between Arabia and Nubia advocated in this work as the main driver of rift localising agrees with the Stratoid being associated to extensional events[17,32], with the primary control on volcanism being rift related adiabatic decompression melting[11].

This work provides precise temporal constraints regarding the process of rift localisation which can help to improve the still poorly defined temporal reconstruction of the rift to drift transition[89,90] (< 10 Ma). In particular, during magma-rich rifting, the transition from broad to narrow rifting and consequent formation of a magmatic segment takes place relatively rapidly (2-2.5 Myrs). Furthermore, this work provides insight into the long-standing debate regarding the role of mantle plume vs plate tectonics during rifting[91,92,10,41]. We showed that variations in the distribution and volumes of the volcanic activity during rift evolution, up to small scale flood basalts-like eruptions, can be induced by tectonic processes (such as pulses in lithospheric thinning) without a significant role played by plume upwelling.

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Data availability

All data that support the finding of this work are presented in the paper and/or in the Supplementary material and available online at *Repository*

Author contributions

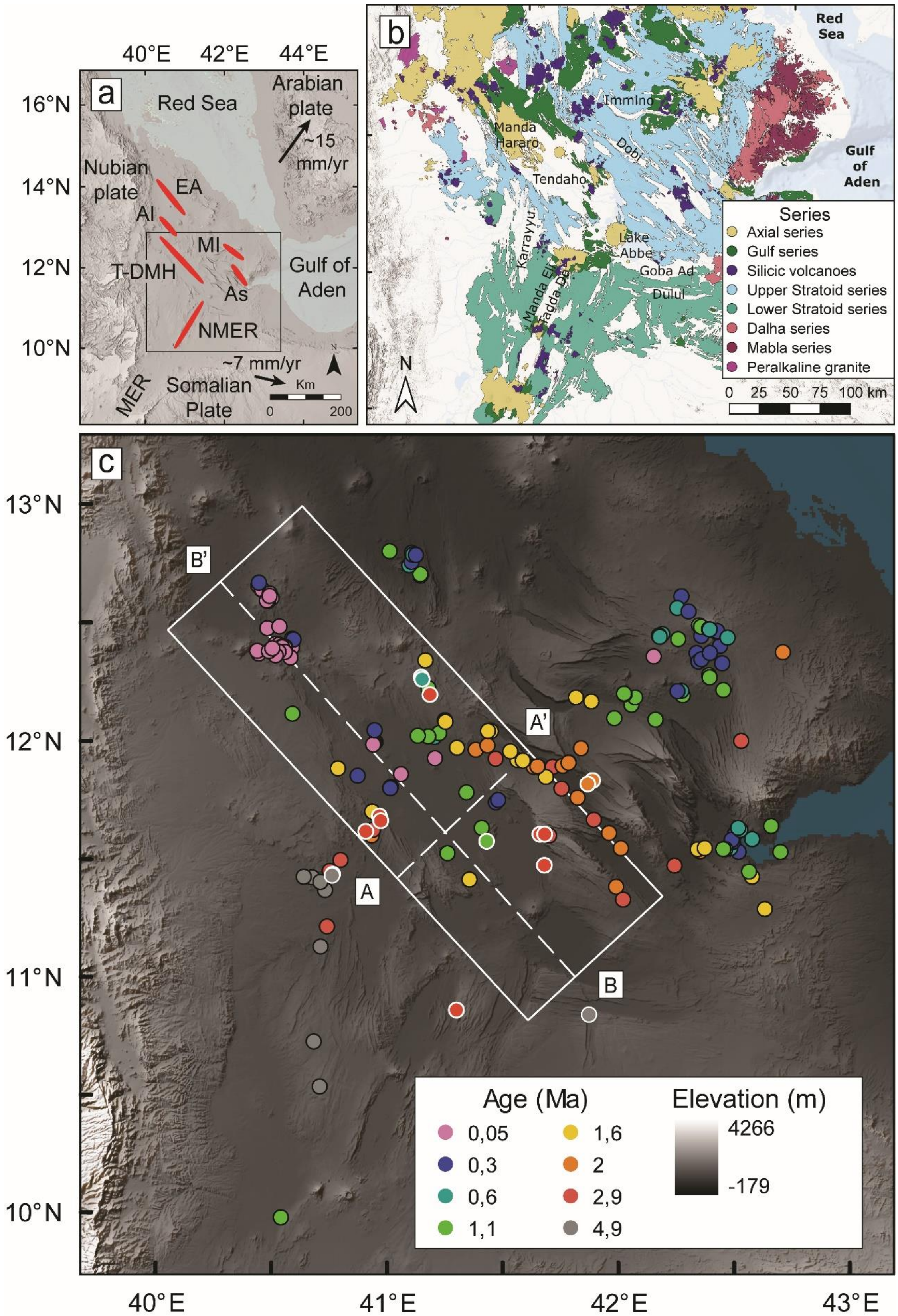
D.K., C.P., G.T. designed the project. G.T., D.K., G.C., E.G. organized the fieldwork. G.T., E.G., D.K., G.C., F.S., A.G. conducted the field trip and helped with sample collection. G.T., D.B., D.M., R.D. prepared the samples for analysis and performed the ^{40}Ar-^{39}Ar analyses and the data corrections. G.T., C. P. compiled the literature dataset. G.T., A.G., D.K., C.P., participated in the interpretation of the data. G.T. wrote the initial version of the manuscript and prepared the figures. All authors contributed to the editing and revision of manuscript and figures.

Competing interests

The authors declare no competing interests.

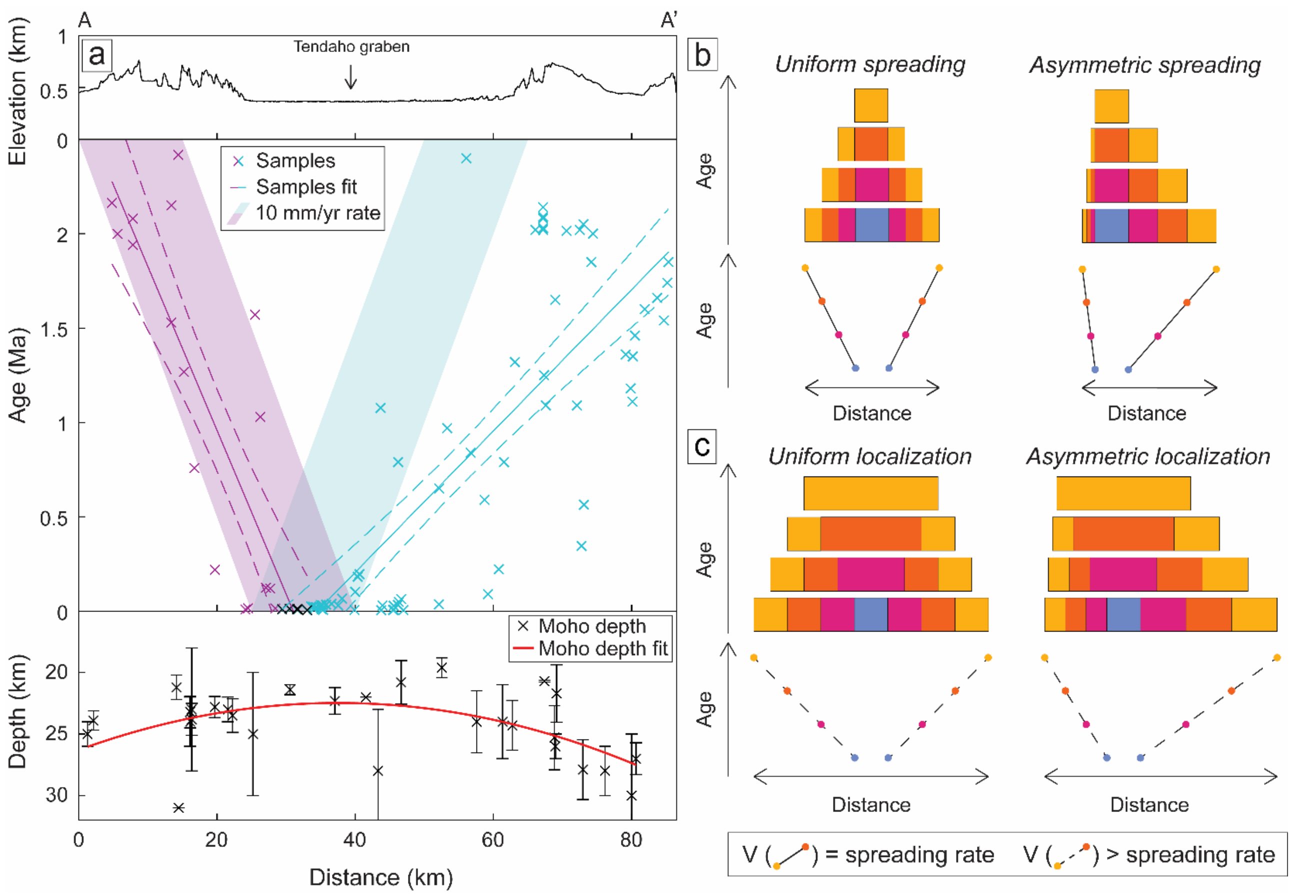
Figures

Figure 1. **Ages distribution of the samples across Afar**



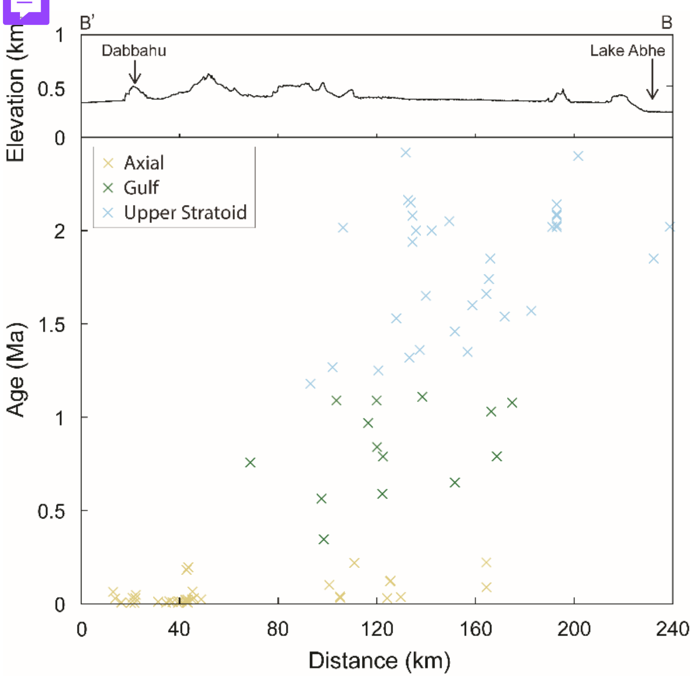
a) Multi-Directional Hillshade map of Afar with magmatic segments in red. Black arrows represent the spreading vector with respect to a fixed Nubian plate. The black box encloses Southern and Central Afar represented in figure (b) and (c). EA, Erta Ale; Al, Alayta; T-DMH, Tendaho-Dabbahu Manda Hararo; As, Asal; MER, Main Ethiopian Rift; NMER, North Main Ethiopian Rift. b) Geological map of Central and Southern Afar from Tortelli et al.[32]. c) Elevation map of Southern and Central Afar with Multi-Directional Hillshade map in the background. All dated samples are coloured based on their age and the new dated samples presented in this work are identified by white rims. The white box identifies the Tendaho-DMH area, enclosing the samples plotted onto across- and along-rift sections (respectively the dashed lines A-A' and B-B') and reported respectively in Fig. 2 and Fig. 3. New data are provided in Supplementary Tab. 1 while literature data[93,94,53,18,58,22,20,21,87,29,19] are in Supplementary Tab. 2.

Figure 2. Across-rift ages distribution of observed and modeled magmatic activity



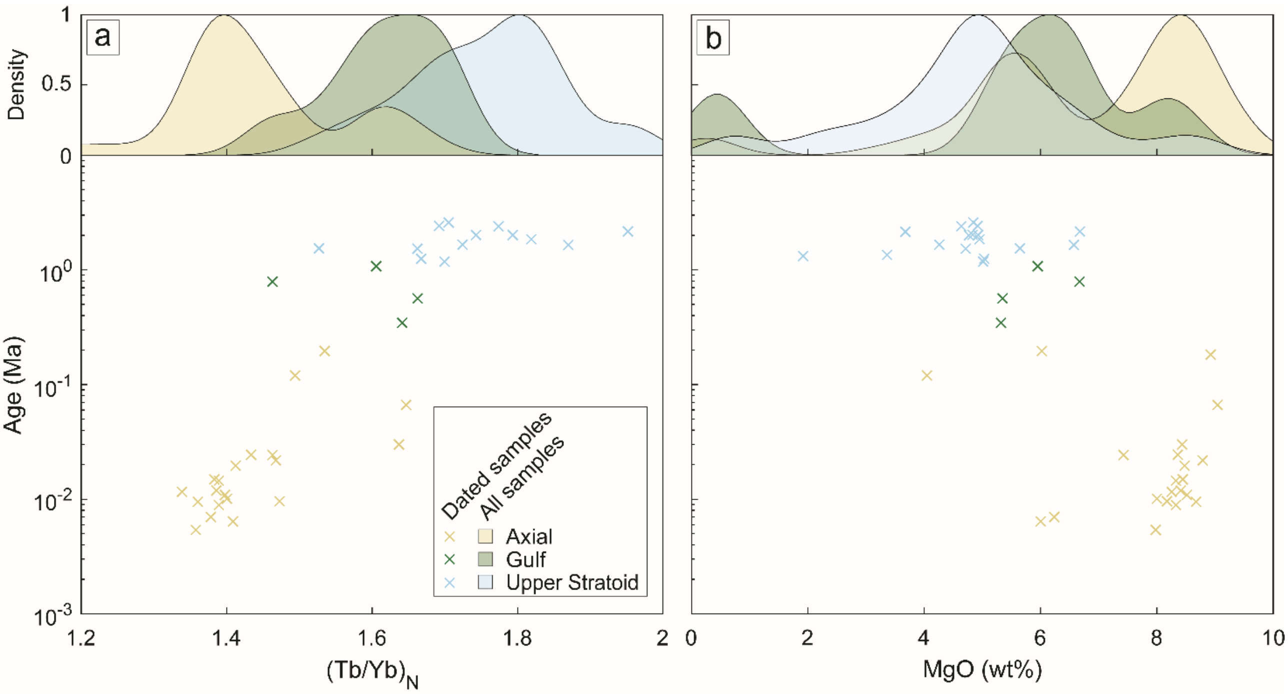
Observed (a) and modelled (b,c) magmatic activity distribution across rift. a) The Top image represents the topographic profile of the A-A' across-rift profile (Fig. 1). The middle image shows the ages of the dated samples projected along the A-A' across-rift profile. The colours identify the samples used to fit the linear regression model (solid lines), purple and pale blue crosses are respectively used for the samples located on the SW and NE side of A-A' across-rift profile while the black crosses had been used for both sides. The dashed lines identify the 95% confidence interval of the linear regression. The calculated rates are 11.5 ± 1.5 mm/yr and 26.7 ± 2.3 mm/yr respectively for the SW and NE side. The inclination of each one of the shaded areas identifies half of the Central Afar extension rate (~10 mm/yr) spanning broadly the Manda Hararo magmatic segment width. The bottom image shows the estimated Moho depths with the errors projected along the A-A' across-rift profile[27,28] (Supplementary Fig. 2). The estimated depths have been fitted by a polynomial curve (red line) to show the crustal thickness variation. b,c) Schematic representations of the eruptive centres areas (i.e., the areas accommodating the extension; colour boxes) during rift spreading (b) and rift localisation (c) with the total extension rate being kept the same for all the models and through time (the top boxes represent the initial stage while the bottom boxes represent the final stage). Below each one of the box models, a graph shows the hypothetical spatial distribution of eruptive centres at their final stages (bottom boxes of each model) to compare them with the real case presented in Fig. 2a. b) for the uniform spreading the width and position of the magmatic segment are fixed. To have asymmetric spreading, different spreading rates for the two sides is needed (in the example is greater on the right side with respect to the left side). c) for the uniform localisation the width of the PBZ gets narrower toward its centre throughout time. To have asymmetric localisation of the PBZ, different spreading rates are needed (in the example it is greater on the right side with respect to the left side). See the text for discussion.

Figure 3. Along-rift ages distribution of the observed magmatic activity



Topographic profile (top) and sample ages (bottom) of the Tendaho-DMH area projected along the B-B' along-rift profile (Fig. 1). The samples are colour coded according to their series as in Fig. 1b. Overall, a decrease in age toward north-west for each series is observed.

Figure 4. Chemical variations of the Afar magmatic activity according to their ages



Mantle- and crustal-related chemical variations of the lava flows samples erupted in the Tendaho-DMH area. a) The Tb/Yb normalised to the chondritic values (McDonough and Sun, 1995) for the mafic samples (MgO > 4 wt%) has been used as a proxy of the depth of the melting column. The upper figure represents the normalized kernel density estimation of all samples according to their respective series while below are reported only the dated samples. The samples are colour coded according to their series as in Fig. 1b. b) Same as figure (a) using the MgO wt% of the samples to evaluate changes in the melt degree of evolution and therefore variations in the magmatic system architecture among the series. See the text for discussion. New data are provided in Supplementary Tab. 1 while literature data[18,32,87,95,23,96,97,98,99,42] in Supplementary Tab. 2.

References

1. White, J. D. L., Bryan, S. E., Ross, P.-S., Self, S. & Thordarson, T. Physical volcanology of continental large igneous provinces: update and review. in *Studies in Volcanology: The Legacy of George Walker* (eds. Thordarson, T., Self, S., Larsen, G., Rowland, S. K. & Höskuldsson, Á.) vol. 2 0 (Geological Society of London, 2009).
2. Holbrook, W. S. & Kelemen, P. B. Large igneous province on the US Atlantic margin and implications for magmatism during continental breakup. *Nature* **364**, 433–436 (1993).
3. White, R. & McKenzie, D. Magmatism at rift zones: The generation of volcanic continental margins and flood basalts. *J. Geophys. Res. Solid Earth* **94**, 7685–7729 (1989).
4. Courtillot, V., Jaupart, C., Manighetti, I., Tapponnier, P. & Besse, J. On causal links between flood basalts and continental breakup. *Earth Planet. Sci. Lett.* **166**, 177–195 (1999).
5. Koppers, A. A. P. *et al.* Mantle plumes and their role in Earth processes. *Nat. Rev. Earth Environ.* **2**, 382–401 (2021).
6. Nelson, W. R., Furman, T., van Keken, P. E., Shirey, S. B. & Hanan, B. B. OsHf isotopic insight into mantle plume dynamics beneath the East African Rift System. *Chem. Geol.* **320–321**, 66–79 (2012).
7. Rooney, T. O., Herzberg, C. & Bastow, I. D. Elevated mantle temperature beneath East Africa. *Geology* **40**, 27–30 (2012).
8. Buiter, S. J. H. & Torsvik, T. H. A review of Wilson Cycle plate margins: A role for mantle plumes in continental break-up along sutures? *Gondwana Res.* **26**, 627–653 (2014).
9. Holbrook, W. S. *et al.* Mantle thermal structure and active upwelling during continental breakup in the North Atlantic. *Earth Planet. Sci. Lett.* **190**, 251–266 (2001).
10. Cawood, P. A., Strachan, R. A., Pisarevsky, S. A., Gladkochub, D. P. & Murphy, J. B. Linking collisional and accretionary orogens during Rodinia assembly and breakup: Implications for models of supercontinent cycles. *Earth Planet. Sci. Lett.* **449**, 118–126 (2016).
11. Rychert, C. A. *et al.* Volcanism in the Afar Rift sustained by decompression melting with minimal plume influence. *Nat. Geosci.* **5**, 406–409 (2012).

12. Gallacher, R. J. *et al.* The initiation of segmented buoyancy-driven melting during continental breakup. *Nat. Commun.* **7**, 13110 (2016).

13. Armitage, J. J. *et al.* Upper mantle temperature and the onset of extension and break-up in Afar, Africa. *Earth Planet. Sci. Lett.* **418**, 78–90 (2015).

14. Brune, S. *et al.* Geodynamics of continental rift initiation and evolution. *Nat. Rev. Earth Environ.* **4**, 235–253 (2023).

15. Hofmann, C. *et al.* Timing of the Ethiopian flood basalt event and implications for plume birth and global change. *Nature* **389**, 838–841 (1997).

16. Wolfenden, E., Ebinger, C., Yirgu, G., Renne, P. R. & Kelley, S. P. Evolution of a volcanic rifted margin: Southern Red Sea, Ethiopia. *GSA Bull.* **117**, 846–864 (2005).

17. Rooney, T. O. The Cenozoic magmatism of East Africa: Part IV – The terminal stages of rifting preserved in the Northern East African Rift System. *Lithos* **360–361**, 105381 (2020).

18. Feyissa, D. H. *et al.* Transition from Plume-driven to Plate-driven Magmatism in the Evolution of the Main Ethiopian Rift. *J. Petrol.* **60**, 1681–1715 (2019).

19. Zumbo, V., Feraud, G., Vellutini, P., Piguet, P. & Vincent, J. First 40Ar/39Ar dating on Early Pliocene to Plio-Pleistocene magmatic events of the Afar, Republic of Djibouti. *First 40Ar39Ar Dating Early Pliocene Plio-Pleistocene Magmat. Events Afar Repub. Djibouti* **65**, 281–295 (1995).

20. Lahitte, P., Gillot, P.-Y., Kidane, T., Courtillot, V. & Bekele, A. New age constraints on the timing of volcanism in central Afar, in the presence of propagating rifts. *J. Geophys. Res. Solid Earth* **108**, (2003).

21. Manighetti, I. *et al.* Propagation of rifting along the Arabia-Somalia Plate Boundary: Into Afar. *J. Geophys. Res. Solid Earth* **103**, 4947–4974 (1998).

22. Kidane, T. *et al.* New paleomagnetic and geochronologic results from Ethiopian Afar: Block rotations linked to rift overlap and propagation and determination of a ∼2 Ma reference pole for stable Africa. *J. Geophys. Res. Solid Earth* **108**, (2003).

23. Barberi, F. & Santacroce, R. The Afar Stratoid Series and the magmatic evolution of East African rift system. *Bull. Société Géologique Fr.* **S7-XXII**, 891–899 (1980).

24. Lahitte, P., Gillot, P.-Y. & Courtillot, V. Silicic central volcanoes as precursors to rift propagation: the Afar case. *Earth Planet. Sci. Lett.* **207**, 103–116 (2003).

25. McClusky, S. *et al.* Kinematics of the southern Red Sea–Afar Triple Junction and implications for plate dynamics. *Geophys. Res. Lett.* **37**, (2010).

26. DeMets, C. & Merkouriev, S. High-resolution estimates of Nubia–Somalia plate motion since 20 Ma from reconstructions of the Southwest Indian Ridge, Red Sea and Gulf of Aden. *Geophys. J. Int.* **207**, 317–332 (2016).

27. Hammond, J. O. S. *et al.* The nature of the crust beneath the Afar triple junction: Evidence from receiver functions. *Geochem. Geophys. Geosystems* **12**, (2011).

28. Ahmed, A. *et al.* Across and along-strike crustal structure variations of the western Afar margin and adjacent plateau: Insights from receiver functions analysis. *J. Afr. Earth Sci.* **192**, 104570 (2022).

29. Stab, M. *et al.* Modes of rifting in magma-rich settings: Tectono-magmatic evolution of Central Afar. *Tectonics* **35**, 2–38 (2016).

30. Acocella, V., Abebe, B., Korme, T. & Barberi, F. Structure of Tendaho Graben and Manda Hararo Rift: Implications for the evolution of the southern Red Sea propagator in Central Afar. *Tectonics* **27**, (2008).

31. Varet, J. *Geology of Afar (East Africa)*. (Springer, 2017).

32. Tortelli, G. *et al.* Constraints on the Magma Source and Rift Evolution From Geochemistry of the Stratoid Flood Basalts (Afar, Ethiopia). *Geochem. Geophys. Geosystems* **23**, e2022GC010434 (2022).

33. Bridges, D. L., Mickus, K., Gao, S. S., Abdelsalam, M. G. & Alemu, A. Magnetic stripes of a transitional continental rift in Afar. *Geology* **40**, 203–206 (2012).

34. Rooney, T. O. *et al.* Upper Mantle Pollution during Afar Plume–Continental Rift Interaction. *J. Petrol.* **53**, 365–389 (2012).

35. Koulakov, I. Yu. Structure of the Afar and Tanzania plumes based on the regional tomography using ISC data. *Dokl. Earth Sci.* **417**, 1287–1292 (2007).

36. Meshesha, D. & Shinjo, R. Rethinking geochemical feature of the Afar and Kenya mantle plumes and geodynamic implications. *J. Geophys. Res. Solid Earth* **113**, (2008).

37. Nyblade, A. A. The upper-mantle low-velocity anomaly beneath Ethiopia, Kenya, and Tanzania: Constraints on the origin of the African superswell in eastern Africa and plate versus plume models of mantle dynamics. in *Volcanism and Evolution of the African Lithosphere* (eds. Beccaluva, L., Bianchini, G. & Wilson, M.) 0 (Geological Society of America, 2011). doi:10.1130/2011.2478(03).

38. Castillo, P. R., Liu, X. & Scarsi, P. The geochemistry and Sr-Nd-Pb isotopic ratios of high 3He/4He Afar and MER basalts indicate a significant role of the African Superplume in EARS magmatism. *Lithos* **376–377**, 105791 (2020).

39. Rajaonarison, T. A., Stamps, D. S., Naliboff, J., Nyblade, A. & Njinju, E. A. A Geodynamic Investigation of Plume-Lithosphere Interactions Beneath the East African Rift. Journal of Geophysical Research: Solid Earth **128**, (2023).

40. Sreenidhi, K. S., Betts, P. G., Radhakrishna, M. & Armit, R. Influence of Lateral Plume Channel on the Evolution of Rift Arms of the Afar Triple Junction: Constraints From 3-D Gravity Interpretation. *J. Geophys. Res. Solid Earth* **128**, e2023JB026791 (2023).

41. Issachar, R., Haas, P., Augustin, N. & Ebbing, J. Rift and plume: a discussion on active and passive rifting mechanisms in the Afro-Arabian rift based on synthesis of geophysical data. *Solid Earth* **15**, 807–826 (2024).

42. Tortelli, G. *et al.* From melt- to crystal-rich magmatic systems during rift localization: Insights from mineral chemistry in Central Afar (Ethiopia). *Contrib. Mineral. Petrol.* (2024).

43. Niespolo, E. M., Rutte, D., Deino, A. L. & Renne, P. R. Intercalibration and age of the Alder Creek sanidine 40Ar/39Ar standard. *Quat. Geochronol.* **39**, 205–213 (2017).

44. Renne, P. R., Balco, G., Ludwig, K. R., Mundil, R. & Min, K. Response to the comment by W.H. Schwarz et al. on “Joint determination of 40K decay constants and 40Ar∗/40K for the Fish Canyon sanidine standard, and improved accuracy for 40Ar/39Ar geochronology” by P.R. Renne et al. (2010). *Geochim. Cosmochim. Acta* **75**, 5097–5100 (2011).

45. Corti, G. Evolution and characteristics of continental rifting: Analog modeling-inspired view and comparison with examples from the East African Rift System. *Tectonophysics* **522–523**, 1–33 (2012).

46. Dunbar, J. A. & Sawyer, D. S. Continental rifting at pre-existing lithospheric weaknesses. *Nature* **333**, 450–452 (1988).

47. Buck, W. R. 1. Consequences of Asthenospheric Variability on Continental Rifting. in *Rheology and Deformation of the Lithosphere at Continental Margins* (eds. Karner, G. D., Taylor, B., Driscoll, N. W. & Kohlstedt, D. L.) 1–30 (Columbia University Press, 2004).

48. Buck, W. R. The role of magma in the development of the Afro-Arabian Rift System. *Geol. Soc. Lond. Spec. Publ.* **259**, 43–54 (2006).

49. Corti, G. *et al.* Transition from continental break-up to punctiform seafloor spreading: How fast, symmetric and magmatic. *Geophys. Res. Lett.* **30**, (2003).

50. Tegner, C., Brooks, C. K., Duncan, R. A., Heister, L. E. & Bernstein, S. 40Ar–39Ar ages of intrusions in East Greenland: Rift-to-drift transition over the Iceland hotspot. *Lithos* **101**, 480–500 (2008).

51. Martin, E. *et al.* Geodynamics of rift–plume interaction in Iceland as constrained by new 40Ar/39Ar and in situ U–Pb zircon ages. *Earth Planet. Sci. Lett.* **311**, 28–38 (2011).

52. Goldstein, S. J., Murrell, M. T., Janecky, D. R., Delaney, J. R. & Clague, D. A. Geochronology and petrogenesis of MORB from the Juan de Fuca and Gorda ridges by 238U– 230Th disequilibrium. *Earth Planet. Sci. Lett.* **107**, 25–41 (1991).

53. Ferguson, D. J. *et al.* Constraining timescales of focused magmatic accretion and extension in the Afar crust using lava geochronology. *Nat. Commun.* **4**, 1416 (2013).

54. Michon, L., Famin, V. & Quidelleur, X. Evolution of the East African Rift System from trap-scale to plate-scale rifting. *Earth-Sci. Rev.* **231**, 104089 (2022).

55. Gianelli, G. *et al.* Water–rock interaction and hydrothermal mineral equilibria in the Tendaho geothermal system. *J. Volcanol. Geotherm. Res.* **86**, 253–276 (1998).

56. Battistelli, A., Yiheyis, A., Calore, C., Ferragina, C. & Abatneh, W. Reservoir engineering assessment of Dubti geothermal field, Northern Tendaho Rift, Ethiopia. *Geothermics* **31**, 381–406 (2002).

57. Wang, K., Plank, T., Walker, J. D. & Smith, E. I. A mantle melting profile across the Basin and Range, SW USA. *J. Geophys. Res. Solid Earth* **107**, ECV 5-1-ECV 5-21 (2002).

58. Field, L., Blundy, J., Calvert, A. & Yirgu, G. Magmatic history of Dabbahu, a composite volcano in the Afar Rift, Ethiopia. *GSA Bull.* **125**, 128–147 (2013).

59. Medynski, S. *et al.* Magmatic cycles pace tectonic and morphological expression of rifting (Afar depression, Ethiopia). *Earth Planet. Sci. Lett.* **446**, 77–88 (2016).

60. Hammond, J. O. S. Constraining melt geometries beneath the Afar Depression, Ethiopia from teleseismic receiver functions: The anisotropic H-κ stacking technique. *Geochem. Geophys. Geosystems* **15**, 1316–1332 (2014).

61. Chambers, E. L., Harmon, N., Rychert, C. A. & Keir, D. Variations in melt emplacement beneath the northern East African Rift from radial anisotropy. *Earth Planet. Sci. Lett.* **573**, 117150 (2021).

62. Desissa, M. *et al.* A mantle magma reservoir beneath an incipient mid-ocean ridge in Afar, Ethiopia. *Nat. Geosci.* **6**, 861–865 (2013).

63. La Rosa, A. *et al.* Simultaneous rift-scale inflation of a deep crustal sill network in Afar, East Africa. *Nat. Commun.* **15**, 4287 (2024).

64. Grandin, R. *et al.* Sequence of rifting in Afar, Manda-Hararo rift, Ethiopia, 2005–2009: Time-space evolution and interactions between dikes from interferometric synthetic aperture radar and static stress change modeling. *J. Geophys. Res. Solid Earth* **115**, (2010).

65. Didana, Y. L., Thiel, S. & Heinson, G. Magnetotelluric imaging of upper crustal partial melt at Tendaho graben in Afar, Ethiopia. *Geophys. Res. Lett.* **41**, 3089–3095 (2014).

66. Hamling, I. J. *et al.* Geodetic observations of the ongoing Dabbahu rifting episode: New dyke intrusions in 2006 and 2007. *Geophys. J. Int.* **178**, 989–1003 (2009).

67. Wright, T. J. *et al.* Magma-maintained rift segmentation at continental rupture in the 2005 Afar dyking episode. *Nature* **442**, 291–294 (2006).

68. Müller, R. D., Sdrolias, M., Gaina, C. & Roest, W. R. Age, spreading rates, and spreading asymmetry of the world's ocean crust. *Geochem. Geophys. Geosystems* **9**, 2007GC001743 (2008).

69. Moore, C., Wright, T., Hooper, A. & Biggs, J. The 2017 Eruption of Erta 'Ale Volcano, Ethiopia: Insights into the Shallow Axial Plumbing System of an Incipient Mid-Ocean Ridge. *Geochem. Geophys. Geosystems* **20**, 5727–5743 (2019).

70. Havlin, C., Parmentier, E. M. & Hirth, G. Dike propagation driven by melt accumulation at the lithosphere–asthenosphere boundary. *Earth Planet. Sci. Lett.* **376**, 20–28 (2013).

71. Bialas, R. W., Buck, W. R. & Qin, R. How much magma is required to rift a continent? *Earth Planet. Sci. Lett.* **292**, 68–78 (2010).

72. Chenin, P., Schmalholz, S. M., Manatschal, G. & Karner, G. D. Necking of the lithosphere: a reappraisal of basic concepts with thermo-mechanical numerical modeling. *J. Geophys. Res. Solid Earth* **123**, 5279–5299 (2018).

73. Petri, B. *et al.* Thinning mechanisms of heterogeneous continental lithosphere. *Earth Planet. Sci. Lett.* **512**, 147–162 (2019).

74. Pilet, S., Baker, M. B. & Stolper, E. M. Metasomatized Lithosphere and the Origin of Alkaline Lavas. *Science* **320**, 916–919 (2008).

75. Rooney, T. O., Brown, E. L., Bastow, I. D., Arrowsmith, J. R. & Campisano, C. J. Magmatism during the continent – ocean transition. *Earth Planet. Sci. Lett.* **614**, 118189 (2023).

76. Ebinger, C. J. *et al.* Crustal Structure of Active Deformation Zones in Africa: Implications for Global Crustal Processes. *Tectonics* **36**, 3298–3332 (2017).

77. Muirhead, J. D. *et al.* Evolution of upper crustal faulting assisted by magmatic volatile release during early-stage continental rift development in the East African Rift. *Geosphere* **12**, 1670–1700 (2016).

78. Hopper, E. *et al.* Preferential localized thinning of lithospheric mantle in the melt-poor Malawi Rift. *Nat. Geosci.* **13**, 584–589 (2020).

79. Alene, M. *et al.* Geochemistry of Woranso–Mille Pliocene basalts from west-central Afar, Ethiopia: Implications for mantle source characteristics and rift evolution. *Lithos* **282–283**, 187–200 (2017).

80. Carter, E. J. *et al.* Volcanic tempo driven by rapid fluctuations in mantle temperature during large igneous province emplacement. *Earth Planet. Sci. Lett.* **644**, 118903 (2024).

81. Natali, C. *et al.* High-MgO lavas associated to CFB as indicators of plume-related thermochemical effects: The case of ultra-titaniferous picrite–basalt from the Northern Ethiopian–Yemeni Plateau. *Gondwana Res.* **34**, 29–48 (2016).

82. Beutel, E., van Wijk, J., Ebinger, C., Keir, D. & Agostini, A. Formation and stability of magmatic segments in the Main Ethiopian and Afar rifts. *Earth Planet. Sci. Lett.* **293**, 225–235 (2010).

83. Ferrante, G., Rivalta, E. & Maccaferri, F. Spatio-temporal evolution of rift volcanism controlled top-down by a deepening graben. *Earth Planet. Sci. Lett.* **629**, 118593 (2024).

84. Sani, F., Ghinassi, M., Papini, M., Oms, O. & Finotello, A. Evolution of the northern tip of Afar triangle: Inferences from the Quaternary succession of the Dandiero — Massawa area (Eritrea). *Tectonophysics* **717**, 339–357 (2017).

85. Dumont, S. *et al.* Rifting Processes at a Continent-Ocean Transition Rift Revealed by Fault Analysis: Example of Dabbahu-Manda-Hararo Rift (Ethiopia). *Tectonics* **38**, 190–214 (2019).

86. Rime, V., Foubert, A., Ruch, J. & Kidane, T. Tectonostratigraphic evolution and significance of the Afar Depression. *Earth-Sci. Rev.* **244**, 104519 (2023).

87. Medynski, S. *et al.* Stability of rift axis magma reservoirs: Spatial and temporal evolution of magma supply in the Dabbahu rift segment (Afar, Ethiopia) over the past 30 kyr. *Earth Planet. Sci. Lett.* **409**, 278–289 (2015).

88. Tortelli, G. *et al.* Evidence of active magmatic rifting at the Ma'Alalta volcanic field (Afar, Ethiopia). *Bull. Volcanol.* **83**, 38 (2021).

89. Ding, W. *et al.* Lateral evolution of the rift-to-drift transition in the South China Sea: Evidence from multi-channel seismic data and IODP Expeditions 367&368 drilling results. *Earth Planet. Sci. Lett.* **531**, 115932 (2020).

90. Larsen, H. C. *et al.* Rapid transition from continental breakup to igneous oceanic crust in the South China Sea. *Nat. Geosci.* **11**, 782–789 (2018).

91. Foulger, G. R. *Plates vs Plumes: A Geological Controversy*. (John Wiley & Sons, 2011).

92. Zhang, N., Dang, Z., Huang, C. & Li, Z.-X. The dominant driving force for supercontinent breakup: Plume push or subduction retreat? *Geosci. Front.* **9**, 997–1007 (2018).

93. Courtillot, V. *et al.* Episodic spreading and rift propagation: New paleomagnetic and geochronologic data from the Afar Nascent passive margin. *J. Geophys. Res. Solid Earth* **89**, 3315–3333 (1984).

94. Daoud, M. A. *et al.* Young rift kinematics in the Tadjoura rift, western Gulf of Aden, Republic of Djibouti. *Tectonics* **30**, (2011).

95. Ayalew, D., Pik, R., Bellahsen, N., France, L. & Yirgu, G. Differential Fractionation of Rhyolites During the Course of Crustal Extension, Western Afar (Ethiopian Rift). *Geochem. Geophys. Geosystems* **20**, 571–593 (2019).

96. Barberi, F., Ferrara, G., Santacroce, R., Treuil, M. & Varet, J. A Transitional Basalt-Pantellerite Sequence of Fractional Crystallization, the Boina Centre (Afar Rift, Ethiopia). *J. Petrol.* **16**, 22–56 (1975).

97. Barrat, J. A. *et al.* Geochemistry of basalts from Manda Hararo, Ethiopia: LREE-depleted basalts in Central Afar. *Lithos* **69**, 1–13 (2003).

98. Ferguson, D. J. *et al.* Melting during late-stage rifting in Afar is hot and deep. *Nature* **499**, 70–73 (2013).

99. Ferguson, D. J. *et al.* Recent rift-related volcanism in Afar, Ethiopia. *Earth Planet. Sci. Lett.* **292**, 409–418 (2010).

I would like to point out that I am a geochronologist, not an expert in structural geology. Therefore, I will focus on the geochronological part, which is anyway the basic scheme for all other considerations.

This paper is an original contribution to the study of the Afar region, based on a fair number of new age data and a far greater number of literature data. The latter are the weak point of the article, as I will discuss later.

The new ^{40}Ar-^{39}Ar analyses expand the number of ages obtained with this method in the area, not many as highlighted by supplementary Table 2, where conventional and unspiked K/Ar data are prevalent. Duplicate ^{40}Ar-^{39}Ar analyses of several samples show on average good reproducibility, with rare exceptions (sample AF20-60b maybe deserves more attention). I find questionable the choice not to use both results of the analyses performed in duplicate. Moreover, on average the errors of the two replicate analyses differ little in percentage terms. The average of the two measurements, having Authors discarded the combination of plateau steps (rows 147÷150), seems to me more appropriate and consistent with the analyses performed. However, the chosen criterion is irrelevant in the regional context in which these ages are used, it could be in other geochronological contexts.

Three out of 16 samples show a consistent difference among isochron ages (with an initial $^{40}Ar/^{36}Ar$ ratio slightly radiogenic) and total integrated age (equivalent to a K/Ar age), the last one is definitely older. Unless this difference is attributed to recoil problems, a hypothesis discarded in the text (rows 21÷24, Supplementary text 1), a doubt arises about the literature K/Ar data used in the model presented by the Authors. By the way, Authors are the first to mention the greater reliability of ^{40}Ar-^{39}Ar technique compared to K/Ar one (Supplementary Text 2) and to discard some literature K/Ar data because newly obtained ^{40}Ar-^{39}Ar are younger. K/Ar ages assume an initial atmospheric $^{40}Ar/^{36}Ar$ ratio, and this is not always true as some analyses in this article also demonstrate. Now K/Ar ages represent more than 50% of the data used in Fig. 2 and 3 for the model.

There is a discrepancy (or I misunderstood) in chapter **^{40}Ar-^{39}Ar geochronology** between the first two rows and the last two rows. You indicate an age range for each of the three series, LS, US and Gu, apparently valid for the entire area according to your sampling criteria. Your new ages highlighted a narrow age gap between LS and US, and a more consistent gap between US and Gu. At the end of the chapter you claim that the volcanic activity was continuous and without overlap among series. If you really sampled the bottom and the top of the series, there are gaps in volcanic activity, and there are problems with several literature K/Ar data. If the mentioned intervals of activities refer only to samples dated in this article, then literature data taken as a whole (Supplementary Table 2) show overlap among series, only the dataset used for figure 2 and 3 don't show overlaps. Please clarify.

Is the selection criterion for the samples in rows 180-181 the only one used? I suggest explaining in much more detail than reported in the text the selection criteria of literature samples used in figures 2 and 3, if there are at least some stratigraphic constraints on chosen samples, and if there are samples excluded because considered unreliable. In other words, a critical evaluation of the literature data is necessary for the use that has been made of them in the article.

The last remark is formal: if I have interpreted the rules of the magazine correctly, methods should be inserted at the bottom of the main text.