nature portfolio

Peer Review File

3.7 billion year old detrital sediments in Greenland are consistent with active plate tectonics in the Eoarchean

Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality

28th Dec 23

Dear Dr Boyd,

Your manuscript titled "3.7 billion year old detrital sediments deposited in fore-arc environment" has now been seen by 2 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

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.

****
In particular, please ensure that the revised manuscript meets the following editorial thresholds:

** Expand your geological background and the discussion on the tectonic setting where the sediments were deposited, including the implications for the sedimentary sequence.

** Expand the presentation and interpretation of your geochemical data analysis, including the presentation of the mixing lines, as suggested by reviewer #1

** Present additional evidence for Eoarchean plate tectonic processes, as suggested by reviewer #2.

****

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:
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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,

Carolina Ortiz Guerrero
Associate Editor
Communications Earth & Environment

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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.

Editorial Policy: Policy requirements (Download the link to your computer as a PDF.)

Furthermore, please align your manuscript with our format requirements, which are summarized on the following checklist:
Communications Earth & Environment formatting checklist

and also in our style and formatting guide Communications Earth & Environment formatting guide .

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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.

If a community resource is unavailable, data can be submitted to generalist repositories such as figshare or Dryad Digital Repository. Please provide a unique identifier for the data (for example a DOI or a permanent URL) in the data availability statement, if possible. If the repository does not provide identifiers, we encourage authors to supply the search terms that will return the data. For

data that have been obtained from publically available sources, please provide a URL and the specific data product name in the data availability statement. Data with a DOI should be further cited in the methods reference section.

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

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Review to Boyd et al.:
Boyd et al. presents a new dataset including structural and geochemical data of a 3.7 Ga old sedimentary core from the Isua Supercrustal Belt. Their main findings are, (i) that the sequence and types of sediments found show that they were deposited in an active margin, and (ii) that the terrigenous sediments originate from a mixed source consisting of around 60% felsic and 40% mafic units.
The paper is well written and illustrated. Furthermore, the topic and data discussed are very timely and of interest to a broad scientific audience, making it suitable for publication in Communications Earth and Environment. However, I find that the discussion regarding the tectonic setting in which the sediments have been deposited lacks detail. It remained unclear to me, why the data speaks clearly for a convergent tectonic setting. As this is the main finding of the paper, I would like to see more explanation on this subject. If the two comments below are properly addressed, I suggest publication of the manuscript.

Tectonic setting: Based on the provided information I see that this sedimentary sequence could have been deposited in Arc-environment. However, I was not able to follow why it could not have been deposited in another tectonic environment. This should be better explained, and eventually giving an example what would be expected for sediments deposited in a tectonic scenario involving a long-lived mantel upwelling. What sedimentary sequence, structure, composition distinguishes the two?

Mixing calculations for sedimentary source rocks: For the mixing calculations (Ti/Zr vs La/Yb) need better explanation of the chosen endmembers including providing the data used for the calculations (individual literature data and calculated average values). Furthermore, the mixing line in Fig.2 has an S-curve shape, which is unlikely to be accurate (unless it is an effect from the log-log scale). I would expect a mixing line that is slightly bend to the right. Furthermore, next to the range of felsic vs mafic mass fraction, I would also add the mean value of the mafic to felsic mass fraction.

Reviewer #2 (Remarks to the Author):

The manuscript submitted by Boyd et al. presents major and trace elemental data for drill core samples of one of the best-preserved Eoarchean (>3.6 Ga) sedimentary units worldwide from the the prominent Isua Supracrustal belt. The unit has been previously gained much attention as it hosts graphitic carbon with d13C anomalies indicative of primitive life exposed. In addition, the unit has been interpreted as presenting Earth's oldest turbiditic sediments. The presented study is to my knowledge the first one on the drill cores that were drilled some years ago to provide a continuous

documentation of the almost unique sequence of that age, not influenced by weathering processes. Therefore, it represents an important archieve of Eoarchean sedimentary processes.

Boyed an co-workers used the chemical data to place constraints on the sourced hinterland of the sediments and developed a more or less coherent model for the depositional setting, providing strong evidence that modern-like plate tectonic processes were in operation during the Eoarchean. This study will gain much attention as there is a large debate on the geodynamic setting in which the Isua supracrustal rocks and the related first continental crust formed. Two different models are advocated involving either uniformitarian or non-uniformitarian models. This study provides evidence for plate-tectonic-like processes early in the Archean, in agreement with previous evidence for such a setting.
However, by saying this, I found some critical points that should be addressed in the manuscript and some additional data may be necessary to proof, if the presented model is valuable. Moreover, I have some critical points on the analytical method used to digest the samples.

- As mentioned in the supplementary material some surface samples gave zircon ages of ca. 3.7 Ga. These sample the younger terrane. A final proof of the model would be, if some zircons in the unit, which are based on their geochemical fingerprint sampling the older TTG terrane with ages >3.8 Ga would be found within the Na-rich units.

- An additional point that is in support of the present model illustrated in Fig. 3 is, that recently reported Lu-Hf garnet ages and detailed petrology and P/T estimates from the same sequence published by Eskesen et al. (2023) in Geology show that the peak metamorphism in the unit was only reached during the Neoarchean and not as claimed before during the early Archean. As terrane amalgamation and crustal thickening was earlier in the adjacent source terranes was earlier, it would not be recorded in the turbidites, which would be in support of the present model of Fig. 3.

- Please provide a bit more information on contacts between units, degree of deformation and metamorphic history of the unit.

- The data of the Sm-Nd isochron age cited from Rosing (1999) Science has never been published in a data table. Hoffmann et al. (2010) GCA published Sm-Nd and Lu-Hf data for the same unit. The data of Hoffmann et al. (2010) from the Rosing (1999) locality should be combined with the Sm-Nd data from Rosing (1999). Interestingly, the samples of Hoffmann et al. (2010) build a group of lower endmember compositions of the isochron, possibly allowing a more precise date isochron date of the unit.
- The microwave digestion of the samples may not have digested refractory phases like zircon or Ti-phases, potentially having an influence on the scatter observed in the Ti/Zr diagram. To avoid this, digestion in Parr Bombs is required. It may not have a big influence here, but parts of the scatter can may be explained by this.

- I would add some additional evidence for Eoarchean plate tectonic processes such as recycling of surface-derived material to the mantle sources of the Isua rocks (e.g., Siedenberg et al., 2016; Lewis et al., 2020).
Overall, the manuscript includes a valuable and important dataset that provides evidence for horizontal tectonic processes during the Eoarchean. After the incorporation and some discussion of the metamorphic history of the unit in the framework of the presented model, it would be much more convincing and in agreement with recent findings. By addressing the above-mentioned details,

I suggest publication of the study after moderate revisions.

Kind regards

Going through the manuscript:

Lines 46-47: The different parts of the sentence do not really fit together. Explain the metamorphic history a bit more detailed and relate the metamorphism reported from the same unit to it (see Eskesen et al. (2023) Geology

Line 51: There is also additional evidence for bacterial processes from nitrogen isotopes indicated from the same unit (see Stüeken et al. 2021 Frontiers in Earth Sciences)

Line 53: Is it clear that these are basin deposits without knowing your model? It could also be deep sea close to a continental shelf.

Line 69: Refer to the core log figure.

Line 74ff: What is the contact between the boninites and the lower sedimentary unit. Is it tectonic and sheared or conformable, or is it not possible to say this?

Line 107: Change the isochron age by recalculating the age including the samples from Hoffmann et al. (2010) GCA and leaving the boninite samples out. Most of the Nd is likely from the adjacent felsic terrane, therefore it may be interesting, if the ininital epsNd overlap with values observed from TTGs (e.g., Bennett et al., 1993; Hoffmann et al., 2011, 2014).

Line 149: Be more clear what differentiation means here. It can be TTG production by differentiation of hydrous mafic melts or partial melting of them or both?

Line 164: The sheeted dyke locality is not too far away and in the adjacent mafic unit or? ‘Elsewhere’ is maybe a bit too unprecise.

Methods: present also major and trace element data for the two measured reference materials! I could not find them in the supplementary material.

Fig. 1: show also a photo of the contact to the boninites.

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Tectonic setting: Based on the provided information I see that this sedimentary sequence could have been deposited in Arc-environment. However, I was not able to follow why it could not have been deposited in another tectonic environment. This should be better explained, and eventually giving an example what would be expected for sediments deposited in a tectonic scenario involving a long-lived mantel upwelling. What sedimentary sequence, structure, composition distinguishes the two?
We have added a brief discussion between line 212 and 222 on why the sediments couldn't be deposited within a long-lived mantle upwelling scenario. From line 223 to 256 we have restructured and added to the discussion concerning why a fore-arc setting best explains our observations.

Mixing calculations for sedimentary source rocks: For the mixing calculations (Ti/Zr vs La/Yb) need better explanation of the chosen endmembers including providing the data used for the calculations (individual literature data and calculated average values). Furthermore, the mixing line in Fig.2 has an S-curve shape, which is unlikely to be accurate (unless it is an effect from the log-log scale). I would expect a mixing line that is slightly bend to the right. Furthermore, next to the range of felsic vs mafic mass fraction, I would also add the mean value of the mafic to felsic mass fraction.

We have added some description and explanation for our choice of end-members and added a supplementary spreadsheet with endmember data and mixing calculations. The S-shaped mixing line in fig. 2 is indeed caused by the log-log scale and would otherwise be asymptotic. We have added the approximate mean felsic fraction to the figure. Further we have added a hypothetical mixing line showing that mixing with boninitic material is not a feasible model for the sediments. A spreadsheet mistake made while making the original figure meant that the La/Yb ratios of the basaltic end-members were wrong. This did not have any impact on the interpretations or conclusion of the study, but has been mitigated in this version. Further, the preferred mixing line is now between TTGs and the combined mafic tholeiitic amphibolites of the ISB (instead of only using the outer arc compositions).

Reviewer #2 (Remarks to the Author):

The manuscript submitted by Boyd et al. presents major and trace elemental data for drill core samples of one of the best-preserved Eoarchean (>3.6 Ga) sedimentary units worldwide from the the prominent Isua Supracrustal belt. The unit has been previously gained much attention as it hosts graphitic carbon with d13C anomalies indicative of primitive life exposed. In addition, the unit has been interpreted as presenting Earth's oldest turbiditic sediments. The presented study is to my knowledge the first one on the drill cores that were drilled some years ago to provide a continuous documentation of the almost unique sequence of that age, not influenced by weathering processes. Therefore, it represents an important archieve of Eoarchean sedimentary processes.

Boyed an co-workers used the chemical data to place constraints on the sourced hinterland of the sediments and developed a more or less coherent model for the depositional setting, providing strong evidence that modern-like plate tectonic processes were in operation during the Eoarchean.
This study will gain much attention as there is a large debate on the geodynamic setting in which the Isua supracrustal rocks and the related first continental crust formed. Two different models are advocated involving either uniformitarian or non-uniformitarian models. This study provides evidence for plate-tectonic-like processes early in the Archean, in agreement with previous evidence for such a setting.
However, by saying this, I found some critical points that should be addressed in the manuscript and some additional data may be necessary to proof, if the presented model is valuable. Moreover, I have some critical points on the analytical method used to digest the samples.

- As mentioned in the supplementary material some surface samples gave zircon ages of ca. 3.7 Ga. These sample the younger terrane. A final proof of the model would be, if some zircons in the unit, which are based on their geochemical fingerprint sampling the older TTG terrane with ages >3.8 Ga would be found within the Na-rich units.

We agree that additional zircon age data would be of great value to our characterization of the sedimentary source terrain, but unfortunately zircons have proven difficult to find and isolate from these lithologies, using standard methods. We hope to be able to find zircons in the future, using more extraneous methods, but currently this material is not available to us.

- An additional point that is in support of the present model illustrated in Fig. 3 is, that recently reported Lu-Hf garnet ages and detailed petrology and P/T estimates from the same sequence published by Eskesen et al. (2023) in Geology show that the peak metamorphism in the unit was only reached during the Neoarchean and not as claimed before during the early Archean. As terrane amalgamation and crustal thickening was earlier in the adjacent source terranes was earlier, it would not be recorded in the turbidites, which would be in support of the present model of Fig. 3.

We refer to the results of Eskesen et al., (2023) in lines 249 to 252 as possibly supporting our tectonic model.

- Please provide a bit more information on contacts between units, degree of deformation and metamorphic history of the unit.

We have added information about metamorphic history in the introduction (line 52 to 56), a short description of the observed deformation and how it pertains to our observations (line 85 to 89) and described the transition between volcanics and sediments (line 96 to 104).

- The data of the Sm-Nd isochron age cited from Rosing (1999) Science has never been published in a data table. Hoffmann et al. (2010) GCA published Sm-Nd and Lu-Hf data for the same unit. The data of Hoffmann et al. (2010) from the Rosing (1999) locality should be combined with the Sm-Nd data from Rosing (1999). Interestingly, the samples of Hoffmann et al. (2010) build a group of lower endmember compositions of the isochron, possibly allowing a more precise date isochron date of the unit.

Unfortunately, we have not been able to recover the raw data used in the Rosing (1999) paper for calculating the Sm-Nd isochron. However, we note that the combined boninite and meta-sediment Sm-Nd data reported by Hoffmann et al. (2010) agrees with our estimated age.

- The microwave digestion of the samples may not have digested refractory phases like zircon or Ti-phases, potentially having an influence on the scatter observed in the Ti/Zr diagram. To avoid this, digestion in Parr Bombs is required. It may not have a big influence here, but parts of the scatter can may be explained by this.

Unfortunately, we do not have local access to Parr bombs, but we will take this into consideration going forward. However, we note that most of our samples have positive Zr-Hf anomalies compared to Nd-Sm, suggesting that, at least, most of the zircon would have been digested. In our supplementary data we have also now added data for our reference material, which shows that Ti values on average were 8 percentage points lower than target values, whereas Zr values on average were 9 percentage points lower. This degree of accuracy is similar to that reported for these reference material in other studies. Additionally, as the reviewer points out, a greater accuracy wouldn't change the median Ti/Zr of our samples or, consequently, our conclusions.

- I would add some additional evidence for Eoarchean plate tectonic processes such as recycling of surface-derived material to the mantle sources of the Isua rocks (e.g., Siedenberg et al., 2016; Lewis et al., 2020).

We have added a paragraph mentioning previous evidence for plate tectonics in the litterature in our second to last section (line 206 to 212), including references to Lewis et al. (2021) and Lewis et al. (2023).

Overall, the manuscript includes a valuable and important dataset that provides evidence for horizontal tectonic processes during the Eoarchean. After the incorporation and some discussion of the metamorphic history of the unit in the framework of the presented model, it would be much more convincing and in agreement with recent findings. By addressing the above-mentioned details, I suggest publication of the study after moderate revisions.

Kind regards

Going through the manuscript:

Lines 46-47: The different parts of the sentence do not really fit together. Explain the metamorphic history a bit more detailed and relate the metamorphism reported from the same unit to it (see Eskesen et al. (2023) Geology

We have deleted the sentence and added a paragraph presenting the geological background of the ISB (line 46 to 56). The ISB lithological make-up and metamorphism is now presented in separate sections within the paragraph. We have also added information about the age of metamorphic events and specific metamorphic ages that have been derived for the sequence in question. There is some debate about the degree and facies of Eoarchean metamorphism in the literature that would be beyond the scope of the current manuscript, but we hope that our revised presentation provides enough context for the presented data.

Line 51: There is also additional evidence for bacterial processes from nitrogen isotopes indicated from the same unit (see Stüeken et al. 2021 Frontiers in Earth Sciences)

We have added this reference and a half sentence presenting its conclusion (line 61).

Line 53: Is it clear that these are basin deposits without knowing your model? It could also be deep sea close to a continental shelf.

Basin is used here in its broadest sense, which could indeed include a deep sea close to a continental shelf. This is more to say that the implication of preserving detrital sediments is that accommodation space was developed, relative to the hinterland.

Line 69: Refer to the core log figure.

A reference to fig. 1 was added (line 81).

Line 74ff: What is the contact between the boninites and the lower sedimentary unit. Is it tectonic and sheared or conformable, or is it not possible to say this?

We have added a description of the transition between the boninites and lower sedimentary unit, emphasizing that the contact is conformable (line 96 to 104).

Line 107: Change the isochron age by recalculating the age including the samples from Hoffmann et al. (2010) GCA and leaving the boninite samples out. Most of the Nd is likely from the adjacent felsic terrane, therefore it may be interesting, if the ininital epsNd overlap with values observed from TTGs (e.g., Bennett et al., 1993; Hoffmann et al., 2011, 2014).

Unfortunately, we have not been able to recover the raw data used in the Rosing (1999) paper for calculating the Sm-Nd isochron. Discussing the Nd-isotopic composition of the sediments compared to that of the TTGs is indeed very relevant and we therefore add this further down in the discussion (line 198 to 204).

Line 149: Be more clear what differentiation means here. It can be TTG production by differentiation of hydrous mafic melts or partial melting of them or both?

We have added discussion detailing what was meant by differentiation and added details regarding work that was done specifically on the ISB lithologies and Itsaq gneiss complex TTGs (line 189 to 195).

Line 164: The sheeted dyke locality is not too far away and in the adjacent mafic unit or? ‘Elsewhere’ is maybe a bit too unprecise.

We have specified that the sheeted dykes are found within the tholeiitic suite of the inner panels (line 229 to 230).

Methods: present also major and trace element data for the two measured reference materials! I could not find them in the supplementary material.

We have added our reference material data underneath our sample data in our “major and trace elemental data” spreadsheet.

Fig. 1: show also a photo of the contact to the boninites.

We have added subfigures 1g and 1h to fig. 1, which depict two sections of the core representing the transition from volcanic boninites to chemical and detrital sedimentation.

28th Feb 24

Dear Dr Boyd,

Your manuscript titled "3.7 billion year old detrital sediments deposited in fore-arc environment" has now been seen by our 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 under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. 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.

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

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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,

Carolina Ortiz Guerrero
Associate Editor
Communications Earth & Environment

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors answered my questions satisfyingly. From my point of view, the manuscript can be published in its current form.

Reviewer #2 (Remarks to the Author):

I have read again the manuscript and the rebuttal of the reviewers comments. The authors did a good job addressing the raised points and significantly improved the manuscript based on the reviewer's comments. The model is now much clearer and the incorporation of the isotope data into the discussion is a significant improvement.
I just noticed that expressions like 'didn't' and 'haven't' have been used in the revised version, which should be expressed as 'did not' and 'have not'.
Overall, I suggest acceptance of this very interesting artice. It provides new views and insights into the geodynamic regime of the Eoarchean in Isua and is therefore of major importance for the ongoing discussion on the onset of plate tectonic processes.

Kind regards

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In line 170, we have changed “haven’t” to “have not”

In line 254, we have changed “didn’t” to “did not”