Response to review comments for the paper titled: "Multiscalar 3D characterisation of the Mid-Norwegian passive margin evolution, Central Norway: A multi-technique approach to unravelling the structural characteristics and tectonic history of offshore basement highs"

Referee 2) Prof. Deta Gasser; Citation: https://doi.org/10.5194/egusphere-2023-2504-RC2

Dear Prof. Gasser,

We wish to extend our sincere gratitude and appreciation for your detailed and thorough review and insightful comments on our manuscript entitled "Multiscalar 3D characterisation of the Mid-Norwegian passive margin evolution, Central Norway: A multi-technique approach to unravelling the structural characteristics and tectonic history of offshore basement highs."

We appreciate the time and effort that you have contributed to our manuscript, and the constructive feedback will be invaluable in improving the quality of the work overall.

We have thoroughly considered each of your suggestions and present our responses and revisions. For context on this response document structure: We have first included the general comments (overall, and then by section as was originally done in the review), with the responses below, and then included the 'in-text' comments from the annotated .pdf, with specific responses.

Overall general comments (summarised):

1. Enhance the presentation of cross-cutting relationships among lineaments, preferably with high-resolution DTM images alongside magnetic anomalies.
2. Improve the introduction and display of structural field measurements, including a stereo plot illustrating both strike orientations and dip values, as well as lineation and kinematic data.
3. Provide a more systematic presentation and interpretation of the K-Ar results on a sample-by-sample basis.
4. Streamline the text by eliminating wordiness and repetitions, condensing the introduction, and ensuring paragraphs in the results section are appropriately categorised.
5. Offer an interpretation of brittle tectonic evolution considering dip values of features and the orientation of lineations and kinematic indicators, building upon the structural field measurements.

Overall general comment responses and revisions made to manuscript:

1. We agree that the presentation of the cross-cutting relationships is insufficient to effectively support our claims on relative timing of the lineaments. We have now both enlarged the main geophysical map in Figure 2A and included only two 'zoom-in' areas in Figure 2B, with both the DTM and geophysical data showing. The 'zoom-in' areas are also at a smaller-scale now to aid in visually seeing the different lineament trends and cross-cutting relationships.
2. We concede that this was a missing component on the original manuscript. We have now included stereonet plots for both the field and drill data, showing pole to plane trends of all the measured planes, slip lineations, and kinematics (coloured by regime). The data have been sorted by deformation episode as derived from the mineral assemblages and cross-cutting field relationships, and integrated with our other field, drill, and petrographic results.
3. We agree that this is a more robust approach to understanding and using K-Ar dates in complex brittle deformed volumes such as Smøla. We have thus reorganised and rewritten the text, systematically characterising each K-Ar sample. Full sample descriptions have been included now in the supplementary material.
4. We acknowledge that the manuscript required significant streamlining and reduction in word count. We have now shortened the introduction, rearranged certain sections (e.g. Basement deformation in 3D), and attempted to cut down the length of the manuscript where possible. However, the inclusion of the requested material (see above) has increased the manuscript length.
5. We agree that the original manuscript lacked sufficient reference to both the field and drill structural data. We have now incorporated this data into the interpretations, using the strike/dip, slip lineation orientations, and kinematics for understanding each of the deformation episodes, particularly where some of the episodes may be comprised of more than one sub-episode of deformation. In most cases, the field data have proven to be more useful for this purpose.

General comment responses by section:

For the specific comments to each section, the reader is referred to the original review at the citation link: https://doi.org/10.5194/egusphere-2023-2504-RC2.

Title:

Response: We agree the title is ambitious. We have decided to adjust the title to "Multiscalar 3D-temporal structural characterisation of Smøla Island, Mid-Norwegian passive margin: an analogue for unravelling the tectonic history of offshore basement highs"

Introduction:

Response: See general comment response above, we agree the Introduction required shortening. We have consolidated the last three paragraphs into a single paragraph as suggested.

Geological Framework:

Response: Please see specific responses below to comments in the annotated pdf.

The Applied Toolbox:

Response: We agree, the field mapping-related methods should be discussed before the drill hole-related activities. We have now moved this portion of text first. Moreover, for the drill holes, we have now included information on the rationale behind the drill hole locations, when they were drilled, and where they are now stored.

Results

Lineament Mapping:

Response: Please also see the specific responses below to comments in the annotated pdf. The lineation trends are now associated with numbers L1 to L8, and the lineaments have been colour-coded and labelled on Figure 2B. We have included each of the lineament descriptions with the location information. Within the text we have highlight difficulties in establishing cross-cutting relations owing to both the resolution of the imagery, and the difficulty in defining the start and end points of the lineaments. The descriptions of the cross-cutting relationships of each lineament set have been rewritten to improve clarity and simplify the text as much as possible. We have also simplified Table 1 to only indicate either termination or cross-cutting relationships, with no indication on strike-slip or dip-slip offsets of one lineament set by another.

Deformation History:

Response: We agree that this section needed a proper and thorough description of the field and drill structural data. We have now included summaries of the structural data within the field, drill, and petrographic results. We have focussed primarily on the field data as it incorporates data from wider areas across Smola than the drill holes. Corresponding to the summaries, we have included a stereonet figure for both the field and drill data sorted by deformation episode. Within the summaries and on the figure, we incorporate kinematic information and trends of both slip lineations and measured planar features (shear features, significant deformation zones, and veins). We have also moved the misplaced paragraph to within the “Basement deformation in 3D” section.

K-Ar Geochronology and X-ray Diffraction:

Response: We agree this section needed a more systematic approach in presenting the K-Ar results. We have therefore characterised and summarised the results for each sample individually and sequentially based on age and deformation episode. A full description of each sample has also been included in the supplementary material. For each sample, we firstly describe the field relationships, then the X-ray diffraction (XRD) mineralogy results, and finally the K-Ar age results. The age results are then discussed relative to the grain size fraction, associated mineralogy, and compared against the other samples. Sample SK1033_1 is particularly discussed due to the possible saprolite formation age it has yielded.

Basement Deformation in 3D:

Response: This section has been rearranged to be before the K-Ar sample section. The text has been reorganised, rewritten, shortened, and simplified, with better correlations between the text and the figure (Figure 8). Figure 8 has also been updated, with the zones discussed in the text colour-coded and number labelled the same as the text.

Discussion:

Response: We acknowledge that primarily using lineaments to demonstrate a tectonic evolution is insufficient. Although the field and drillhole structural data was utilised in the study, the lack of visual evidence was an issue. We therefore have now incorporated the structural data in the deformation history discussion and toned down the use of lineaments (we have still correlated the lineaments to the structural data where possible). We have also brought in the shallow structures as seen in the drill holes into the interpretations (including the 3D modelling work). Associating the structures to the absolute age data (K-Ar ages) has now been done taking the individual samples into account, and the specific grain size fractions within the samples. The final section of the discussion regarding Frøya High has been significantly shortened and Table 5 has been removed. This section is now intended to convey the importance of using onshore analogues, such as Smola, in understanding offshore basement highs.

Conclusion:

Response: We have rewritten the conclusions based on the revised manuscript, incorporating the new information regarding the field and drill structural data, and the systematic K-Ar sample descriptions and interpretations. The abstract has been similarly rewritten with a focus on the amended results and interpretations of the study. The abstract has also been streamlined and shortened with less emphasis on the project background and rationale.

Annotated comments within the text:

The referee comments within the manuscript are included below with the page number and line number of the original annotated manuscript. Below each referee comment, we provide our response, and our change(s) made within the new revised manuscript.

Title

Page 1, line 1: See suggestion for alternative title in the separate reviewer file

Response: See general comment response above.

Introduction

Page 2, line 45: This part is not absolutely necessary, could be omitted for shortening. shorter: " their size is commonly below seismic resolution"

Response: We agree. A selection of the text has now been removed, and text changed to suggested.

Page 2, line 60: shorter: "is an ideal analogue for basement highs offshore..."

Response: We agree. We have changed the text to the suggested.

Page 3, line 62: Long sentence, shorter would be: "At Smøla, a wealth of local and regional structures are preserved, which document the tectonic evolution of the margin through time".

Response: We agree the sentence can be shorter. Text changed to "Smøla itself possesses a wealth of preserved local and regional structures, which document the tectonic evolution of the margin through time."

Page 3, line 66: Brittle

Response: We agree. Text changed to suggested

Page 3, line 67: add Hestnes et al. 2022 (https://www.sciencedirect.com/science/article/pii/S0191814122001134?via%3Dihub) and Tartaglia et al 2020 (https://www.sciencedirect.com/science/article/pii/S0012821X20303642) and Scheiber et al. 2019 to this list (https://www.sciencedirect.com/science/article/pii/S0191814118305029)

Response: We agree. We have now inserted these references into the text.

Page 3, line 70: I am not sure your approach is so new. Most of the previous studies cited above use lineament mapping, extensive field observations including mineralogy and K-Ar fault gouge dating (e.g. Scheiber/Viola, Hestnes and Tartaglia)- the only thing that might be new are the boreholes, but the tools used there (macro- and microstructural observations) are not particularly new. I suggest you combine the last three paragraphs of the introduction into one single paragraph, shortening the context considerably and avoiding repetition (the methods are mentioned twice, both in the second and third paragraph), stating that you present a detailed case study applying known methods to a particular area.

Response: We agree, and we have updated the text to highlight the new perspective offered by the drill holes. A concluding point on the relevance of this work in the offshore realm and the implications on generating deterministic inputs for fracture modelling is also included. This is important as this paper will lead on to the next paper currently in production which relates to this aspect specifically. Revision: Text updated to "…a new 3D perspective from four diamond drill holes on Smøla Island, we present a case study that describes and tests a comprehensive workflow for characterising onshore basement blocks."

Geological framework

Regional perspective

Page 3, line 90: placed along

Response: Text changed to "set along", as the island is not necessarily "placed" which implies a positioning of the island after the formation of the passive margin.

Page 4, line 93: The Scandian phase is usually assumed to cover the time span from ca. 430-400 Ma

Response: Text changed to "(430 to 400 Ma)" to reflect the time span.

Page 4, line 99: Text deleted

Response: We agree, text deleted

Page 4, line 102: Devonian

Response: we agree, Text updated

Page 4, line 104: Insert also Grønlie&Roberts 1989 and Grønlie et al. 1994.: Fission-track and K-Ar dating of tectonic activity in a transect across the Møre-Trøndelag Fault Zone, central Norway. Norsk Geologisk Tidsskrift. Vol. 74, pp. 24-34.

Response: we agree, inserted the references

Page 4, line 105: Text deleted

Response: We agree, text deleted.

Page 4, line 107: Fig. 1B

Response: We agree, and we have inserted the figure reference.

Page 4, line 114: which time? The time of break-up just described above? Or the entire Devonian-Paleogene time? Specify/rewrite

Response: We have merged the paragraph with paragraph above, which provides more clarity on the time span. Rewrote to remove the uncertainty regarding the time span.

Page 4, line 114: when does a passive margin actually form? I would say at break-up? Before it is just a continent with rifts? Consider rewriting

Response: We agree, we have rewritten it to remove the uncertainty regarding the formation of the passive margin.

Page 5, line 120, Figure 1: Separate out the supracrustals (limestones, volcanics)?

Response: We agree, and now the limestone and volcanics on Figure 1B have been separated out and given their own symbology.

Page 5, line 120, Figure 1: Use brownish colors for gabbros and metagabbros, blueish colors are usually used for carbonates

Response: We agree, and now on Figure 1B all the lithology types have been recoloured with appropriate colours based on the Geological Survey of Norway colour scheme.

Page 5, line 120, Figure 1: Baltica autochthonous

Response: we agree, and the text in Figure 1A has been changed.

Page 6, line 132: not shown on map? Remove

Response: We agree, the text has been removed.

Page 6, line 135: consider placing the reference at the end of the sentence for better readability

Response: Yes, we agree, we have moved the reference.

Page 6, line 138: Text deleted (comma)

Response: We do not agree. The comma must remain, as it is a list, and for consistence with the reminder of the text, the authors are using the Oxford comma convention.

Geological framework

The geology of Smøla

Page 6, line 143: those are not separated out on the map in Fig. 1b - it would be nice to show them with an own color on the map (now they are combined with the gabbro?) since those are the only Caledonian supracrustal rocks on the island

Response: We agree, and now these units are separated in Fig. 1B, with their own colour symbology.

Page 6, line 145: Check the reference style - the "H." and "Ha." has to be removed I guess

Response: We acknowledge this problem; the reference is now corrected.

Page 6, line 151: which fill in

Response: Yes, we agree. The text changed to the suggested

Page 7, line 160: Does not fit here - can be included in the last paragraph of the introduction

Response: We agree, but we have decided to entirely remove "In comparison to the MTFC and the wider margin, the post-Caledonian structural evolution of Smøla remains poorly investigated and understood.", as it is not relevant to the purpose of the paper, where we are highlighting a methodology of characterising basement rock volumes.

The applied toolbox

Page 7, line 173: It is more logic to describe the field methods first, and then the drill hole logging.

Response: We agree, particularly as the majority of the logged features in drill core are centimetric in scale.

Page 7, line 174: Say something about the drill cores - when where they taken and why? What was the reason for placing them where they are? Were they conducted during your own study, or are these older cores?

Response: The four diamond drill holes used in this study were drilled in 2019 during a previous NGU project (BASE 2). The drill holes were designed to target major structures, and sample weathered basement rocks. We have updated the text to reflect this.

Page 7, line 178: Move this to the start of the paragraph

Response: We agree, and we have moved it to the start of the paragraph.

Results

Lineament mapping from geophysics and DTM data

Page 8, line 196: Refer to the supplement/data repository where the lineaments are available as geodatabase

Response: We agree, and we have added a reference to the supplementary data repository

Page 8, line 197: I cannot see that different magnetic blocks were discussed above? Consider rewriting

Response: We agree, the text has been rewritten.

Page 8, line 201: use this numbering in the table 1 and in the text below, so orientation trend 1) is N-S, 2) is NW-SE, 3) is E-W etc.

Response: We agree, this has been added into the text and the Table 1 has been updated.

Page 9, line 206, Figure 2: It is very difficult to see the domain boundaries - how where the lineaments assigned to the different domains? Consider using thicker white lines to delineate the domain boundaries

Response: We agree, the boundaries have been made to be thick white lines to improve the clarity.

Page 9, line 206, Figure 2: It is hard to see the outline of the island/coast - could it be an idea to make the submarine areas more transparent (or putting a whitish transparent layer on top of the submarine areas, to that the magnetic pattern appears weaker in color?)

Response: Yes, we agree it is difficult to determine on/offshore areas. The areas covered by the Norwegian Sea have been now represented by a transparent white layer above the geophysics imagery.

Page 9, line 206, Figure 2: I am not so convinced about these cross-cutting relationships. The thick black NW-SE trending line could easily be drawn across the thinner, SW-NE trending line (the magnetic anomaly continues across it), so to me it is not clear that the northern black line is the same as the southern

Response: We somewhat agree with your comment, the insert does not particularly show the entire context of that lineament placement for this particular case. However, there is both a high amplitude anomaly flanking the NE-side of the NW-SE lineament, and a possible remnant magnetised/de-magnetised zone to the SE of lineament. Both features were used to guide the location of the lineament. Additionally, the magnetic fabric to the NE appears to be offset over the NE-SW lineament. Lineament mapping using airborne magnetic data is interpretive, but if the mapping is completed in a consistent method, considering specific features in the magnetic data, this is the best possible interpretation. The authors do concede, owing to the interpretive nature of this work, that it is possible that the lineament could be mapped differently by another. The text has been overall rewritten for this section, and this has been removed.

Page 10, line 221: You do not highlight NNW-SSE lineaments in Fig 2BI, so it is difficult to follow your argumentation here

Response: We agree with the need to improve clarity, as such we have highlighted the lineaments in Figure 2B by colour, and labelled the associated rose diagrams.

Page 10, line 225: how do you constrain dip-slip offset from 2D lineament mapping?

Response: We have removed reference to this in the text, as it does have high uncertainty, and will use the other structural data (field and drill hole) to discuss. But a dip-slip offset on a 2D map is a possible interpretation when a magnetic anomaly changes in width (apparent thickness) over a cross-cutting lineament (suggesting a different portion of the magnetic unit is providing a geophysical response). This is a similar method of interpretation as used in reading geological maps. It is not possible to get this interpretation from DTM imagery.

Page 10, line 226: Move this information to the start of the N-S trend description

Response: We agree, the text has been updated to the suggested.

Page 10, line 228: I do not see any convincingly dextrally offset lineaments on this figure - can you point at a particular lineament that you can trace to the right north of the E-W lineament?

Response: We agree, the text has removed.

Page 10, line 228: dip-slip is difficult to constrain on 2D maps

Response: We agree, the text has removed.

Page 10, line 229: Again, you have to point at particular lineaments which you think are offset, since I do not easily see the offsets you describe in the pattern, which shows many cross-cutting, but not offsetting, lines

Response: We agree that the small ‘zoom-in’ inserts with geophysical imagery are not sufficient for showing the offsets. We have now selected two optimal areas with the most examples of lineament cross-cutting relationships. The ‘zoom-in’ images are also at a smaller scale (more ‘zoomed-in’) with both the DTM and geophysics shown. Moreover, we have decided to simplify the text and discuss cross-cutting rather than offsetting relationships, except in very clear examples.

Page 10, line 232: Move this to the start of the NW-SE trend description

Response: We agree, the text has been moved to the beginning of the description.

Page 10, line 235: The HSF is NE-SW trending. Do you assume sinistral or dextral movement along this when considering Riedel orientation? If you assume sinistral movement, and sigma 1 oriented 45 degrees to the fault (approximately N-S), then the Riedel (R, not R prime) orientation would be NNE-SSW. If you assume dekstral movement, sigma 1 would be approximately E-W, so the Riedel orientation would be WSW-ENE - which situation do you envisage here?

Response: We concede that this is too uncertain, and too interpretive for this part of the manuscript, so we have removed the reference to Reidel shears. The lineaments could be splay off the MTFC as Reidel shears or just other potential structures which have formed during a different tectonic episode. The latter is more likely. As such, the possible lineament offsets will be interrogated/compared against the structural data later in the discussion.

Page 10, line 237: This figure looks more like the E-W lineaments cross-cut all the others?

Response: We agree, the figure has now been changed and the text rewritten. The NW-SE, NNE-SSW, and NNW-SSE lineaments do appear to crosscut the E-W lineaments. In the discussion, we suggest that this may be a later reactivation of these features.

Page 11, line 238: Does that mean that the N-S, NW-SE and E-W lineaments all cross-cut each other at some point and it is not possible to say who is oldest/youngest? Be more specific here

Response: We agree that the text is too ambiguous, so it has been rewritten. Where these lineaments are third-order lineaments, they, they are crosscut by the other lineament trends in a similar way. This would suggest that they may be relatively early lineaments. Second-order E-W lineaments crosscut almost all other features, suggesting they continued to develop until later.

Page 11, line 242: Move this to the start of the description

Response: Yes, we agree; the text moved as suggested.

Page 11, line 246: again, you have to point out specific offset lineaments, on Fig. 2BV I noly see straight lines that crosscut the NE-SW lineaments.

Response: We agree. The text has been updated to emphasis cross-cutting relationships rather than offset, and a new figure insert in Fig 2 has been included to highlight these cross-cutting relationships (see general comment above).

Page 11, line 249: Move this to the start of the orientation description

Response: We agree; the text has been moved as suggested.

Deformation history

Page 11, line 257: Rename this into for example "field and drill hole results", or separate into two chapters, 4.2. Structural field measurements and 4.3. Deformation history based on mineralogical relationships" or something similar, based on how you decide to restructure your text based on my comment in the separate reviewer file

Response: We largely agree with this comment. We have now changed the title to “Field, drill hole, and petrographic results”, as the petrographic work was a significant component of these results.

Page 11, line 258: Here you jump directly from the lineament mapping to the borehole scale, and skip the entire field station part! I highly recommend you start your result description with a summary of what your field stations have revealed - se detailed comment in the separate reviewer file.

Response: We concede that this is a significant gap in the results section. Therefore, we have now included summaries of the field structural results along with the relevant field, drill, and petrographic hole observations. These summaries are included by deformation episode and mineral-assemblage. We have decided to nestle the structural data results within the text to improve flow and limit repetition.

Page 11, line 260: They are not properly presented in the current manuscript, and should come prior to the cm-scale borehole observations!

Response: We have included a detailed figure with stereonets displaying all planer, lineation, and kinematic data. Both the field and drill data has been included.

Page 12, line 273, Figure 3: would it be possible to color code the structural measurements according to D1-D5?

Response: Unfortunately, this is not possible. We have included this information in the previous figure and will keep the figure as is. This figure is intended to indicate the distribution of collected data, and the variability of structural geometries downhole.

Page 12, line 283: this has to be documented by a proper stereonet figure showing plane and lineation measurements

Response: We agree. This has now been included the within the Field, drill hole, and petrographic results section.

Page 14, line 309: This is again easier to state if you can refer to a stereonet figure

Response: We have now included a reference to the stereonet figure.

Page 14, line 323: refer to a stereonet figure

Response: We have now included a reference to the stereonet figure.

Page 14, line 327: Strike through

Response: Agreed, text removed.

Page 14, line 327: which subfigure?

Response: We agree this is missing, text modified to "Figure 5E"

Page 14, line 328: stereonet figure - orientation of slicken lines or other lineations associated with it?

Response: This has now been included the within the Field, drill hole, and petrographic results section, and shown on Figure 3.

Page 15, line 329: has to be documented with lineation measurements and kinematic indicators

Response: We agree, and this has now been included within the Field, drill hole, and petrographic results section. Removed from current position.

Page 15, line 333: **Fig 5.** Specify the samples and/or field stations/drill cores the pictures are coming from - it can be a good idea to add coordinates behind each field and thin section photograph (see figure caption of Hestnes et al. (2022))

Response: Yes, we agree with this. We have included the coordinates (UTM)/Drill hole and depth for the samples within an additional document within the supplementary material. We have also included a reference to this in the paper.

Page 16, line 347: orientation data

Response: This has now been included in the within the Field, drill hole, and petrographic results section, and shown on Figure 3.

Page 16, line 364: lineations and kinematic indicators

Response: This has now been included in the within the Field, drill hole, and petrographic results section, and shown on Figure 3.

Page 16, line 368: if they are well-consolidated, they are not really gouges longer? If they have a cohesion, they might be ultracataclasites?

Response: Yes, this may be true, but in this case, the gouge is indurated/cemented with hematite/Fe-oxides. So, the level of consolidation is secondary. We have amended the text to make this clearer.

Page 16, line 368: Strike through

Response: Agreed, removed “on average”

Page 17, line 380, Figure 6: It would be great to have such a figure as a stereonet, also with associated mineral lineation data plotted.

Response: This has now been compiled for Figure 3 with stereonets for each deformation episode.

Page 18, line 414: "on average" is strange wording in this context. If you have 10 planes dipping 90 degrees and 10 planes dipping 0 degrees, the average dip becomes 45 degrees? You probably mean that most measurements fall within 30-70 degrees, but that is not an average value - I suggest you remove "on average"

Response: Yes agreed. We have removed this phrase from the text.

Page 16, line 415: kinematic indicators?

Response: This has now been included the within the Field, drill hole, and petrographic results section, and shown on Figure 3

Page 19, line 433: The following four paragraphs (until the subchapter 4.3.) are out of place - they deal with correlations of particular features in the boreholes shown in Fig. 10, and should entirely be moved to and incorporated into the text in chapter 4.4

Response: Yes, we apologise, these paragraphs are misplaced. We have moved and rearranged them with the section “Basement deformation in 3D”.

K-Ar geochronology and X-ray diffraction

Page 20, line 466: Thats the aim - but how can you document/make sure that your fractions only contain authigenic and synkinematic clay?? This has to be argued for for each sample carefully

Response: We have now characterised each of the samples systematically, with commentary on the composition of each of the grain size fractions. A full description and characterisation is now available in the supplementary material.

Page 20, line 470: The composition of the different fractions for each sample has to be introduced better - which fractions do most probably only contain illite or smectite, whereas which fractions do probably contain a mixture of illite/smectite and inherited muscovite, K-fsp etc.? This is crucial for the age interpretation.

Response: As stated above, we have now characterised each of the samples systematically, with comments on both the composition of each of the grain size fraction, and also the potential source of the minerals. This will be used later in the discussion to further argue for the age interpretations.

Page 20, line 476: thats too general - introduce the dates for each fraction from each sample systematically, and discuss their geological significance

Response: Yes, we agree, therefore we have introduced each of the samples' K-Ar ages, by the grain size fractions. With a focus on the most geologically significant size fractions. This is typically the finest and the coarsest, but where the age spectra curve deviates from an inclined curve, we have added comments on this (i.e. where there is an older/younger age which is not associated with the coarsest and the finest fractions).

Page 21, line 480: this statement needs a reference and/or better explanation

Response: Yes, we agree this needs a reference. We have included the reference of Levy & Woldegabriel (1995), which discusses the loss of radiogenic ^{40}Ar from a zeolite (clinoptilolite).

Page 21, line 481: You have to discuss that systematically for each sample, since the mineralogical composition for each sample and each fraction is different

Response: Agreed. We have introduced each of the samples' XRD results prior to outlining the K-Ar dating results. This has been done by mineral type and by grain size fraction.

Page 22, line 493: respectively

Response: Agreed. Text removed and rewritten.

Page 23, line 496: This is way too generalized. The three youngest finest fractions actually scatter from ca. 70 to 130 Ma potentially belonging to very different deformation phases (e.g. see the discussion of calcite ages at 140, 90-80 and 70-60 in Hestnes et al.). If you argue properly for each sample and why you think the youngest fraction is geologically meaningful, you then can extract much more information from this data than just the three broad belts at 100, 200 and 300.

Response: We have removed this text, as we agree it is too generalised and simplistic. The different samples are now presented with their relevant K-Ar ages. From the XRD and K-Ar geochronology work we now have the following date groups ~287 – 291 Ma, 196 – 204 Ma, 100 – (128?) Ma, and 75 Ma.

Page 23, line 497, Figure 9: Once you have argued properly and systematically for each sample, you can highlight those dates which you think are geologically meaningful - this might be all the finest fractions (74, 99, 128, 196, 201, 204) and maybe a plateau in the coarsest fractions for sample SK2008 at ca 200, but this depends on the mineralogical interpretation of these fractions (inherited or authigenic?). You should remove the three belts at 100, 200 and 300, which are confusing and not precise enough

Response: We have included the dates we feel are geologically meaningful and updated the figure. The belts are in place to highlight clustering of dates for the finest fraction. The earlier large fraction dates for SK2012 and SK2015 are also highlighted as these two different structures provided two very similar dates. We have now included a belt for the youngest age for sample 120714, as this age provides an upper limit for the D4 mineralisation.

Page 24, line 505: With

Response: We agree, the text has been removed.

Page 24, line 507: Consider replacing this with a figure showing the mineralogical content of each fraction from each sample. This information has to be placed before the age information

Response: The figure has been replaced by a series of pie chart graphs for each sample and by grain size fraction. The figure has been furthermore moved to before the K-Ar dating information.

Page 24, line 514: Should come before the age presentation, should be done systematically sample for sample

Response: Agreed. This portion of the text has been integrated into the individual sample characterisations and moved to be before the K-Ar geochronology information.

Page 25, line 525: this has to be introduced and discussed better: do you think this could be a deep weathering zone, not necessarily related to deformation, but to deep infiltration of surface fluids? So the age of ca. 128 Ma for the two finest fractions could represent Cretaceous deep weathering? How would that fit with deep weathering proposed elsewhere along the margin (if I remember right that was supposed to be in the Jurassic?)

Response: It is always possible that percolating meteoric/ground water has penetrated down and along inclined structures. The overall zone is saprolitic, so the age of the finest grain size fraction may well be authigenic clay growth related to saprolite development. However, weathering along the western portion of the Norwegian passive margin (and particularly along the Strand flat) is typically associated with Jurassic times (e.g. between ~221 Ma to 206 Ma for Bømlo, Western Norway) (e.g. Fredin et al., 2017; Olesen et al., 2023). As SK1033_1 has returned a Cretaceous age, there may well be a hydrothermal component to the age.

Basement deformation in 3D

Response: This section has been moved to before the K-Ar geochronology and XRD section.

Page 27, line 558: the 3D model in the middle of Fig 10A shows more than four green planes - it is not so easy to identify the four planes which occur in both bore holes from this plot - could it be an idea to colour the four planes which occur in both cores with a different colour?

Response: We agree that this figure is not clear, and well-correlated with the associated text. We have updated the figure, with the zones colour-coded by deformation episode. The zones mentioned in text have now also been labelled I, II, III, IV to aid identification from what is written in text.

Page 27, line 560: here you say a D1 zone occurs in both B1 and B2, but in the Figure, the planes are all green, where the legend says these are D2 zones - could it be an idea to color the planes according to whether they are D1, D2 etc. features? Out from your description in the text here (zones I to IV i struggle with clearly identifying them in the figure. Could it be an idea to also mark them with I to IV in Fig. 3?

Response: As stated above, the figure has been updated, with the zones colour-coded for deformation episode. The zones mentioned in text have now been labelled I, II, III, IV to aid identification from what is written in text.

Discussion

Polyphase evolution of Smøla and the passive margin

Page 27, line 579: abbreviation not used earlier? Explain

Response: We acknowledge this comment. The text has been removed from the update manuscript.

Page 27, line 581: Such orientations are very minor in Fig. 6 D1, where D1 seems to be dominated by E-W lineaments, so I am not sure what you are referring to here?

Response: These lineament trends are potential early D1 features owing to the cross-cutting and termination relationships. We have amended the text to reflect this better.

Page 27, line 585: ENE-WSW cannot vary from NNE-SSW to NW-SE?

Response: We agree. Text removed; it was attempting to show the range in strike trends.

Page 27, line 587: how do you get local folding and contraction during sinistral transtension? within a restraining bend?

Response: We acknowledge that this is a controversial issue. Works done by Bøe & Bjerkli (1989) and Fossen (2010) (and references within), suggest that there was a N-S contraction of the Devonian Basin adjacent to the MTFC during Mid to Late-Devonian times (based on folds with E-W trending axial traces, and reverse faults). This contraction may have occurred syn-kinematically with strike-slip movement on the MTFC, or if transtension on the MTFC occurred, either before or after this phase. If before, these contractional features may have rotated as they approached the MTFC trace (Fossen, 2010). A portion of the D1 structural data, however, does fit with this contraction direction.

Page 28, line 594: the youngest fractions in the D2 samples are 200 Ma, which possibly can be interpreted as the formation age of the gouges/shear fabrics - the significance of the coarsest fractions at 300 Ma is much less clear, and if you would like to assign those a geological significance, you have to argue for it properly in the results section (maybe the two oldest fractions in 2012 and 2015 make some sort of meaningful plateau?) ->but I would definitively place D2 around 200 Ma, and not 300 Ma based on the youngest fractions

Response: We have adjusted the text to focus mostly on the ~200 Ma age associated with the finest fractions of the samples SK2012, SK2015, and SK1029_1. However, the clustering of dates at ~300 Ma for the size fractions 2-6 and 6-10 μm for the samples SK2012 and SK2015, does suggest that there is distinct inherited component in the K-Ar ages. Considering the differences in both structure orientations and mineral composition (minor difference) in the coarser fractions of these samples, it would be expected that there would be more age difference, particularly if the potassic feldspar in SK2015 afforded a protolithic component. As there is not, there may be an earlier Carboniferous-Permian deformation episode preserved in these deformation zones. The microstructural evidence also suggests that there are two preserved events in the zones.

Page 28, line 595: Fig 6 shows that E-W is minor for D2, but NW-SE is quite important?

Response: Yes, on the rose plots the E-W trend is not visible enough. These structures correlate to the major E-W lineaments (L3). However, the new stereonet plots in Figures 3, do show the importance of the E-W structures. The text has been updated to reflect this as well.

Page 28, line 596: just speculation/correlation with what others have said before?

Response: Yes, we are correlating the findings with the associated literature to try fit our findings within what others have found. This part of the D2 section has been rewritten, to explain how the structures with sinistral kinematics and the associated K-Ar ages can be compared and correlated with the relevant literature.

Page 29, line 603: In this entire discussion of lineaments and orientations it would be really useful to have the real structural data plots, not only lineaments. From the borehole plots it is obvious that many of the structures have a quite shallow dip, which is of importance if one wants to relate them to the basically steep MTFC faults! You should also discuss this in the light of your own kinematic indicators and lineations from the field, not only somewhat ambiguous offsets from the lineament maps.

Response: We agree it is important to integrate the field and drill hole structural data, and as we have stated before, these datasets are now included in the Discussion section.

However, regarding the shallow structures in the drill holes:

Importantly, the drill hole data probably contains more shallow than steep features owing to line-sampling bias (e.g. Terzaghi, 1965).

Most of the shallowly dipping D2 structures come from drill holes BH3 and BH4. These holes intersect several foliated gneiss and diorite units. Most of the shallowly dipping features correspond to slip along pre-existing foliation planes (with chlorite being present) within particularly micaceous intervals.

The drill holes BH1 and BH2, are mostly in massive monzogranite, and are situated north of a significant E-W structure, which locally shifts to a NW-SE trend.

The geometry of the features in BH1, BH2, therefore may rather stem from local stress perturbations (in terms of orientations of the principal stress axes, and stress magnitude) within the damage zone of a major structure (e.g. Kim et al., 2004). Or, if assuming these features are shallow thrusts, they may have formed due to local shortening (transgressive faulting) owing to the strike rotation of the major E-W structure, forming a restraining bend (assuming sinistral kinematics) (e.g. Cunningham & Mann, 2007). As visually demonstrated in the 3D modelling, the D2 structures dip S towards the steep major E-W structure. They may therefore represent either antithetic or conjugate features forming in an extensional setting (which have later rotated to shallower dips), although confirmation is challenging without kinematics of the modelled structures, and resolving the geometry of the major E-W structures (assumed to be steep to sub-vertical).

We have updated the text to include reference to the field and drill hole structural data, and 3D modelling.

Page 29, line 616: But the 200 Ma ages seem to come from very shallow structures (<30degrees) - how does that fit with P- and R-shear dextral strike-slip models based on lineaments?

Response: We somewhat agree, however only the sample SK2012 comes from a structure dipping at <30 degrees. The other two samples SK2015 (36 degrees), and SK1029_1 (80 degrees), show that a variety of structures were experiencing fluid flow and authigenic activity at ~200 Ma. Nonetheless we have rewritten this section to remove the correlation with P and R-shears which would indeed require steep to sub-vertical structures.

Page 29, line 618: that would imply subvertical structures, but your measurements in the boreholes are all quite shallow - these geometries do not look like a classic strike-slip setting?

Response: We agree that the shallow structures in the drill holes are problematic for a strictly strike-slip interpretation. The shallow structures related to the later D2 deformation are likely to be conjugate or antithetic features off the steeply dipping/sub-vertical structures. These structures would have had to have formed in an extensional setting. We have rewritten the text to take the geometries of the structures into account. Particularly, the 3D modelling.

Page 29, line 622: you mean ridge-push? its either ridge-push or slab-pull - I dont think there was a slab around at that time anywhere in the North Atlantic, but there was not ridge either until the Paleogene, so what do you mean here? Far-field effects from the Alpine slab? Along which margin - there was no margin at that time yet?

Response: Yes, we meant ridge-push. The suggestion that possibly ridge-push forces may have induced dextral strike-slip on the MTFC comes from studies looking at later tectonic cases (such as the Cenozoic for Pascal & Gabrielsen (2001)). We concede that this is too distant in time from the Triassic-Jurassic, so we have removed this from the text.

Page 29, line 625: I would try to have a look at the entire structural data set - what are your dip values saying, what are your mineral lineations saying? Are we in an extensional setting with flat-lying structures developping mostly reactivating older foliations (reactivation phase of Peron-Pindivic etc.)? Are the lineations subhorizontal or down-dip? The lineament maps alone do not tell us the entire story

Response: We agree this is the best approach. We have rewritten the section to incorporate this information within the text.

Page 29, line 628: what do you mean with authigenic here? Which mineral? And I would say that all your three D3 samples provide finest fraction ages between 120 and 74, not between 200 and 100 - so once you have described and interpreted your 7 samples more carefully, you can be more precise here.

Response: The authigenic age we used, related to the growth of clay minerals within the samples. We agree this is not the best use of the term considering the larger size fractions for the samples SK2008 and SK1033_1 may well include protolithic/inherited material which would not be authigenic. We have updated the text to be more specific based on the new systematic descriptions of the D3 samples.

Page 29, line 629: can you see such a transition in your data? be more specific on what your orientation and kinematic data say about the D3 phase - in order to do that, you have to present your stereoplots including lineations/kinematics.

Response: The proportion of the structures which exhibit dip-slip (mostly normal to oblique-normal) kinematics compared to D2 is significant. This indicates to us that there was a change in the overall tectonic regime over Smøla. The ~N-S reverse faults, and dextral features provide some limited evidence (along with the work of Bøe and Bjerkli (1989)) in suggesting that there was some possible dextral strike-slip during the later D3 episode. We have updated the text to present the structural data for D3.

Page 30, line 629: what are your field measurements on D3 structures telling?

Response: Most of the D3 structures are dip-slip features. We have updated the text to state this.

Page 30, line 647: where comes this from? shouldnt it maybe be 128 Ma?

Response: The text was reflecting the largest size fraction age within the relative age of the zeolite veins. This is unnecessary, so we have updated the text to just reflect the age of the smallest size fraction (~75 Ma).

Page 30, line 660: Hestnes worked north of Sognefjorden, which I would not call SW Norway (which is Rogaland etc.)

Response: We agree, the text has been updated to describe it as W Norway rather.

Page 30, line 662: possibly related to the

Response: Agreed, text has been updated to the suggested.

Page 30, line 666: how do you really know which lineaments are associated with the different D phases, since many orientations occur in all phases (e.g. Fig. 6?) I understand that you can assign a fracture/fault observed in the field to one of the phases due to the mineralogy, but a lineament on a map, without groundtruthing, is probably difficult to uniequivocally assign to a D phase?

Response: We have previously used the cross-cutting relationships and strike trends of the different D's to sort the lineament trends. We agree that this is not a very robust method, and we have now updated the text to include the structural data from the field and drill holes to improve the interpretation and sorting. Realistically, the lineaments are likely to have formed and then been reactivated during multiple deformation episodes. The shallowly dipping structures are also not typically represented by the lineaments. However, the orientation and cross-cutting relationships do convey a structural evolutionary story.

Page 31, line 670: Text removed

Response: We agree, text removed.

Page 31, line 674: here the dip-values of these features are again crucial

Response: We are keeping the text the same, as now the D5 features being “sub-parallel” means both the strike trends and the dips are similar to the bounding structures around the Frøya High.

Application to and implications for the Frøya High offshore domain

Page 31, line 677: I am not sure this title is very suited for the content of this chapter - what you discuss is basically an outlook on how onshore detailed field studies can help understanding offhore basement bodies, but that additional methods (permeability modelling etc) are needed to constrain parameters relevant for hydrocarbon exploration. Maybe a title could be "Smøla as an analogue model for similar offshore basement areas and possible future research" or something similar?

Response: I agree and have adjusted the title accordingly to “Smøla as an analogue for similar offshore basement volumes”. The purpose of this section is to try connecting this work with basement volumes offshore, with the Frøya High being the most applicable given the similarity in both basement geology and structural/tectonic history.

Page 31, line 678: consisting of similar basement rocks as Smøla

Response: The section has been rewritten, with this comment incorporated in the new text.

Page 32, line 706: could your saprolite sample be an example of weathered basement?

Response: This is possible. However, the K-Ar age of the saprolite sample, being significantly different to the results from other studies may not make this sample the best to use for this purpose. Further work focussing on specifically weathered basement rocks on Smola may answer this question.

Conclusions

Page 32, line 714: I am still not convinced that the approach is particuarly important or new from this study, but the detailed and careful field and borehole observations are definitively very valuable, so I would focus more on that aspect

Response: We agree, the new component of this study relates to the four drill holes. We have therefore removed the mention of a "new" approach from the text. Moreover, the conclusions concentrate on the field, drill hole findings, with the K-Ar dating, lineament mapping results also highlighted.

Page 32, line 717: These conclusions should be updated once the field structural data including lineations and kinematics is included, and dip orientations have to be taken into account (the shallow dips pointing at not only strike-slip dominated deformation?)

Response: Yes, we agree, the findings and the discussion of these findings have been significantly amended with additional information regarding the structural data. We have updated the text of the conclusion accordingly.

Page 32, line 725: ?

Response: Yes, we concede this is too speculatory (see response above), so we have removed mention of slab and ridge-push from the text.

Page 32, line 741: Has to be updated after a careful evaluation of each sample/fraction

Response: We agree on this, and have updated the text to include the following age intervals based on the systematic evaluation of each of the samples: ~287 – 291 Ma (early D2), 196 – 204 Ma (late D2, early D3?), 100 – (128?) Ma (D3), and 75 Ma (upper age cut-off for D4).

We would like to extend our gratitude once again to Prof. Gasser for her invaluable contributions to the improvement of our manuscript. The detailed and rigorous suggestions have been carefully considered, and where possible, we have made corresponding revisions to update the work. We are confident that these adjustments will strengthen the overall quality of the manuscript.

Yours sincerely,

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