Review Report

Nordbäck et al. Mesoproterozoic Strike-Slip Faulting within the Åland Rapakivi Batholith, Southwestern Finland, TEKTONIKA, 2024.

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1st Round of Revisions

Decision Letter

Dear Nicklas Nordbäck, Pietari Skyttä, Jon Engström, Nikolas Ovaskainen, Jussi Mattila, Ismo Aaltonen:

Thank you for submitting your manuscript to Tektonika. We have now reached a decision regarding your submission to тектоніка, "Mesoproterozoic strike-slip faulting within the Åland rapakivi batholith, southwestern Finland ".

At Tektonika we operate a system whereby an Associate Editor, in this case Laura Federico, handle review collection and assessment. You can see Laura's assessment below, which summarises key aspects of the manuscript. In additiont to this summary, I have read through the manuscript and reviews, and agree with their assessment. Overall, the manuscript will be an excellent addition to Tektonika, but we have some recommendations for imporvement prior to publication; these are outline below.

Kind regards,

Craig

------- Associate Editor letter

The manuscript entitled "Mesoproterozoic strike-slip faulting within the Åland rapakivi batholith, southwestern Finland" which you submitted to Tektonika has now been referred.

The manuscript provides an interesting reconstruction of brittle tectonic evolution between ~1.55 and 1.2 Ga in the Åland rapakivi granite batholith in southwestern Finland and provides an example on this type of use of structural data at several different scales.

You presented a large and high-quality data set and built a tectonic evolution of the region that appears reasonable and fit the geodynamic context.

Both the Reviewers acknowledge these positive aspects and agree that the manuscript deserve publication after revisions.

In particular, according to Reviewer1, the text could be edited to be more succinct and easier to read, especially with regard to the “Geological background” and the final section of the discussion sections (5.3).

Most of the pertinent features described in the text are illustrated with comprehensible photos and figures. However, according to Reviewer1, some of them needs improvements (please refer to comments of the Reviewers) and Reviewer2 suggested to add a series of tectonic and geodynamic model map combining with reconstruction the paleo-stress fields of the studied area during different geological times.

Regarding the interpretation of the fault-slip data, both Reviewers identified some points that need to be addressed/discussed. In particular:

1) the use of fault kinematic as a paleostress vs paleostrain indicator and the assumption of isotropic medium (Reviewer1)

2) the math behind the stress analysis (Reviewer2)

3) the age of faulting and the re-activation of older faults (Reviewer2).

I personally would also suggest to clarify how the data are sorted in sub-sets (paragraph 4.4.1, lines 479-480): is it this the result of an inversion done by the software on the full dataset or is it based on observed field features (cross-cutting relationships, mineralizations, etc.)?

To reinforce conclusions and broaden the potential impacts of the paper the suggestion of Reviewer2 to clarify the reasons of the changes in the stress regime should be addressed. This also would help to fit your results into the geodynamic scenario also to the readers not familiar with the specific regional geology.

As final recommendation, tabulated structural data should be provided in the supplementary data, as suggested by Reviewer1.

Comments by Reviewer B (Nicolas Harrichhausen)

See the attached review form and annotated manuscript.

Comments by Reviewer C (Maryam Ezati)

I think the article entitled "Mesoproterozoic strike-slip faulting within the Åland rapakivi batholith, southwestern Finland" can be published after revisions and authors response to the following questions:

I suggest authors provide more detailed formulas and math behind stress analysis in the method and data section, it will help better clear the methods for readers. Authors can use this paper: Ezati M, Gholami E, Mousavi SM (2020) Paleostress regime reconstruction based on brittle structures analysis in the Shekarab Mountain, Eastern Iran. Arab J Geosci 13:1232.

Can author explain why these stages of evolution in stress regimes has happened and what has been behind such stress change?

I suggest authors can add a series of tectonic and geodynamic model map combining with reconstruction the paleo-stress fields of the studied area during different geological times.

There is a general question that should be discussed more thoroughly in the paper. This is a problem problem of age of faulting that arises in all the faulted areas where the paleostress techniques are applied. The problem is that each new tectonic stage can produce faulting or re-activation of faults in older units. The basic criticism that faults observed in for example Mesoproterozoic formations to not indicate that these faults were active in Mesoproterozoic times. They could be of much younger age. By starting with faults in the youngest formations you can be sure that these did not form at an earlier time. But then proceeding back in time how can you eliminate the youngest faults in older terrains? Is it by their orientation in space? The authors do not present compelling evidence how this problem is solved. For answering this question authors can use this paper: Ezati M, Rashidi A, Gholami E, Mousavi S.M, Nemati M, Shafieibafti Sh, Derakhshani R (2022) Paleostress Analysis in the Northern Birjand, East of Iran: Insights from Inversion of Fault-Slip Data, minerals 12:1606.

Authors' Reply to Reviewers

Mesoproterozoic strike-slip faulting within the Åland rapakivi batholith, southwestern Finland

Dear Editor,

Thank you for the constructive comments, they provided a significant contribution to improve our manuscript, of which we now submit a revised version to be evaluated for publication.

We have conducted an extensive revision of the manuscript according to the recommendations. In the following, we provide a detailed explanation of the changes made. We also highlighted the changes within the revised manuscript using "track changes" function in MS Word.

Figures (manuscript and appendices) are provided in vector format as pdf. files. Tables including all structural fault data and joint data has been included as two excel files.

On behalf of all authors,

Nicklas Nordbäck

Comments by reviewer B and Authors' reply

Section A: Overview of manuscript

A1) Overall evaluation, general comments & summary

A1.1) Reviewer's comments

A1.1.1) General evaluation and publication suggestion – Required:

Please use this space to describe, in your own words, the core subject of the submission and your overall assessment of its suitability for publication.

"Mesoproterozoic strike-slip faulting within the Åland rapakivi batholith, southwestern Finland" from Norbäck et al., presents results from a structural study of multiple generations of faults and joints in the Åland rapakivi granite batholith in southwestern Finland. The authors use fault kinematics and joint orientations to interpret regional paleostress conditions during between ~1.55 and 1.2 Ga. They also use regional bathymetric and geophysical data to relate these paleostress orientations and fault formation with regional structures formed during prior tectonic episodes. Given the tectonic interpretation and methodology this is a useful publication that provides insight on the tectonics of the study area, and provides an example on this type of use of structural data at several different scales. However, the manuscript is long and complicated at times, and therefore could use some rewriting and reorganization to simplify the text. In addition, the core premise of using fault kinematic as a paleostress indicator has been challenged as erroneous in at least one recent study, and this, along with the potential for error in interpretation, needs to be more fully addressed in this paper. I therefore recommend some significant revisions.

A1.1.2) What does the submission need to be publishable? (select as needed; comment for all cases)

- ☐ No changes required
- ☐ Rewriting
- ☐ Reorganising
- ☒ More data/figures
- ☒ Condensing
- ☒ Reinterpretation
- ☐ Other

Comments:

Condensing and more figures (or addition to figures): The text does not need a full rewrite, however several sections could be shortened by being more concise and removing information that does not directly relate the results of the paper. For example, the geological introduction is very thorough, but the number of geologic names and events is hard to follow, so it is unclear to the reader how relevant all of the information is. To make this section easier to understand, a figure with the regional geology and a tectonistratigraphic column (maybe as an addition to Figure 1) could be used to help visualize the tectonic relationships. The intro text could then be based on around this figure. The final section of the discussion is also difficult to follow and could use more organization.

Reinterpretation: The main interpretations are pretty good, however there should be some more discussion of why fault kinematics can be used to interpret paleostress orientations. The authors argue that they can assume an isotropic medium when interpreting their data, however, given they are arguing for reactivation and mapping complex fault zones, this assumption does not seem to hold. Once any fault or fracture is formed, the rock is no longer mechanically isotropic. Stress conditions around faults have been shown to change rapidly in magnitude and orientation over short distances and short time spans, and at least one publication has argued that kinematic data is never a good proxy for paleostress conditions (Riller et al., 2017 “Fault-slip inversions: Their importance in terms of strain heterogeneity, and kinematics of brittle deformation”). However, given the consistency of the authors’ data, they may argue that it must be representative of a fairly uniform faulting regime and thus probably results from a relatively uniform stress field. Given the authors are basing most of their interpretations off of this assumption, it should be addressed in the discussion.

A1.1.3) Can the submission be improved by reducing/adding any of the following? (select as needed; comment for all cases)

☒ Text

☒ Table

☒ Figures

☐ Supplementary material

Comments:

Reducing text: see comments above.

Tables and figures: some of the details in the figures need better explanation or they should be removed. Some legends are missing.

A1.1.4) Please complete the following section if you recommend that the

submission is NOT appropriate for publication (select as needed; comment if a box is selected)

- ☐ Quality is poor
- ☐ Research is not reproducible
- ☐ Other

Comments:

A1.2) Author(s) Responses:

The geological background and other parts of the paper was condensed by removing of some information not directly related to the results of the study.

Figure 1 was modified; age information was added to better visualise the tectonostratigraphic relationships between different units. Other figures were also updated based on the annotated comments.

We agree that local strain vs. regional stress requires some discussion, consequently, we have now dedicated a paragraph to this at the beginning of the discussion. We understand that the method of stress inversion has inherent uncertainties but believe that the studied rapakivi is quite optimal in this regard due to the following: 1) the anorogenic rock lacks ductile anisotropies that could affect fault localisation (at least for the small fault structures we have mapped), 2) the oldest brittle structures within the Mesoproterozoic rapakivi must thus have been formed in a rock lacking pre-existing structures, although we interpret that the largest faults within the rapakivi batholith (observed only as lineaments) resulted from reactivation of pre-existing Paleoproterozoic deformation zones within the host rocks to the rapakivi batholith 3) The results are uniform for the region we have mapped, especially regarding Stage 1, 4) The data density should be high enough to identify possible local variations and 5) since a large portion of the data represents small faults and faults that have not experienced large displacements and faults within relatively intact bedrock we regard the impact of local block rotations or stress perturbations as small.

Geodynamic/tectonic maps were added to Figure 12 (as suggested by reviewer C), we think section 5.3 is now easier to follow.

A2) Summary of main merits and main points of improvement

A2.1) Reviewer's comments

Please describe below in a few sentences (100 to 300 words) the main merits of the submission and suggestions for improvements.

The main merits I have found are...

- The interpretations are based on a large and high-quality data collection and all aspects of the data are thoroughly presented and interpreted.
- The interpretations are reasonable and fit within the tectonic context.
- The second to last figure showing the tectonic evolution of the region is very well done and brings together the interpretation well.

The main points of improvement I have found are...

- The text could be edited to be more succinct and easier to read.
- The interpretations are based off an assumption that the studied faults formed in a mechanically isotropic medium. Given the time scale over which they formed, and the nature of faulting itself, this assumption cannot be true. This contradiction warrants some more discussion. Potentially these results can show that this assumption does not need to be made, making the paper more significant in terms of a general contribution to the study of structural geology.
- There are several small interpretations that could be very easily explained by different phenomenon (see line by line edits on the annotated manuscript).
- Some of the figures are hard to see and are missing details and/or explanations in the caption.

A2.2) Author's responses:

All sections of the manuscript were assessed and when possible condensed by removing of information not directly related to the results of the study.

Regarding assumption on isotropic medium, see response to 1.2.

Figures were improved based on the annotated comments, see replies to annotated comments.

Section B: Detailed evaluation of manuscript

B1) Title and abstract

B1.1) Reviewer's comments

These statements are a ***guide*** *to what good* Titles *and* Abstracts include*. Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

The *Title* describes the main topic of the manuscript **accurately — [YES**] / [NO]

The *Title* describes the main topic of the manuscript **succinctly — [YES]** / [NO]

The *Title* includes **appropriate key terms — [YES]** / [NO]

The *Abstract* includes a **clear aim and rationale — [YES]** / [NO]

The *Abstract* supports the rationale with **sufficient background information — [YES]** / [NO]

The *Abstract* includes a **well-balanced description of the methods — [YES]** / [NO]

The *Abstract* describes the **main results sufficiently and adequately — [YES]** / [NO]

The *Abstract* clearly describes the **importance/impact of the study** — [YES] / **[NO**]

The *Abstract* clearly states the **conclusions of the study — [YES**] / [NO]

The *Abstract* is **clear** and **well structured — [YES]** / [NO]

Comments:

The abstract could use a short sentence describing the broader impact of the study.

B1.2) Author's responses

Good suggestion, added the following sentence at the end of the abstract:

“As such, this study contributes towards understanding the relationships between magmatism and strain localisation in continental (failed) rift settings.”

B2) Introduction

B2.1) Reviewer's comments

These statements are a ***guide*** *to what good* Introductions *include. Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

The *Introduction* provides **sufficient background and context** for the study — **[YES]** / [NO]

The *Introduction* describes the **aim/hypothesis/rationale** clearly, providing **sufficient context** — **[YES]** / [NO]

The *objective/hypothesis/rationale* **flows logically from the background** information — **[YES]** / [NO]

The *Introduction* describes the study's **objective and approach** (last paragraph) — **[YES]** / [NO]

The *Introduction* contains **relevant, suitable citations** — **[YES]** / [NO]

The *Introduction* is **organized effectively** — **[YES]** / [NO]

Comments:

The last paragraph of the introduction, while thoroughly describing approach, might be too detailed. The most important aspects of the approach can be integrated into paragraph above and the rest can probably be removed.

B2.2) Author's responses

Agree. We have now removed the last paragraph and integrated parts of it into the paragraphs above.

B3) Data and methods

B3.1) Reviewer's comments

*These statements are a **guide** to what good* Method *sections include and good practices for* Dataset *accessibility. Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

The *Methods* are described **concisely and with enough detail** for reproducibility — [YES] **/ [NO]**

Necessary information about **data sources/acquisition/processing** is included **— [YES]** / [NO]

Data used are accessible via either supplementary files or links in the data availability statement — [YES] / **[NO]**

The *Dataset and/or Methods* are **organized effectively** — **[YES**] / [NO]

Comments:

See comments above about paleostress assumptions.

The methods section is quite long, and could be more succinct.

The orthophotos and other raster images are provided, but in order for the kinematic inversions to be fully reproducable, tablulated structural data should be provide.

B3.2) Author's responses

See response to 1.2

Some unnecessary lines were cut out from methods section. However, section 3.3 was extended as recommended by both reviewers.

Tables including all structural fault data and joint data has been included as supportive material.

B4) Results

B4.1) Reviewer's comments

These statements are a ***guide*** *to what good* Result sections *include. Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

The *Results* findings are **supported by data** — **[YES]** / [NO]

The *Results* findings are presented **clearly and succinctly** — **[YES]** / [NO]

The text in the *Result* section **cites tables and figures appropriately** — **[YES]** / [NO]

The *Results* directly **relate to the study objectives** — **[YES]** / [NO]

The *Results* present **data for all the approaches** described in the *Methods* section — [YES] / **[NO]**

The *Results* **text belongs to the Results section**, not to *Introduction*, *Methods*, or *Discussion.* — **[YES]** / [NO]

The *Results* section is **organised effectively** — **[YES]** / [NO]

Comments:

The figures need some work on cleaning up the details. The structural data, e.g., fault plane orientations, fault slickenline lineations, en echelon fracture orientations, should be provided in the supplement or the database.

B4.2) Author's responses

Figures were improved based on the annotated comments.

Structural data now provided in the supportive material.

B5) Discussion and conclusions

B5.1) Reviewer's comments

These statements are a ***guide*** *to what good* Discussions *and* Conclusions *include. Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

The *Discussion* is **focused on the objectives** of the study — **[YES]** / [NO]

The *Discussion* **addresses all major results** of this study, which are shown in *Results* — **[YES]** / [NO]

The *Discussion* section makes **comparisons with other studies** that are relevant and informative — **[YES]** / [NO]

The *Discussion* section properly identifies all **speculative statements** — [YES] / **[NO]**

The *Discussion* section presents the **implications of the study** persuasively — **[YES]** / [NO]

The *Discussion* section **highlights novel contributions** appropriately — **[YES]** / [NO]

The *Discussion* section **addresses the limitations** of the study appropriately — [YES] / **[NO]**

The *Discussion* section is **organised effectively** — [YES] / **[NO]**

The *Conclusions* are **consistent** with and **summarise** the rest of the manuscript — **[YES]** / [NO]

The *Conclusions* are **supported by the data** in *Results* and **follow logically** from the *Discussion* — **[YES]** / [NO]

The *Conclusions* are **clear and concise** — **[YES]** / [NO]

Comments:

See comments above about discussing assumptions more thoroughly. Other interpretations are fairly speculative. For example, see line by line comments for Line 733.

The final paragraph of the discussion is difficult to follow. It could be broken up into smaller paragraphs.

B5.2) Author's responses

See responses above and responses to the annotated comments.

The final part of discussion (5.3) was clarified by changing some of the wording, by adding more references to figures and by adding geodynamic maps to Figure 12 (representing different Mesoproterozoic tectonic stages, as requested by reviewer C).

B6) Figures, tables and citations

B6.1) Reviewer's comments

*These statements are a **guide** to what good* Figures *and* Tables *include and how they are presented. Please select YES or NO to the statements below if you wish and detail in the free form box below your reasons for any box checked with NO, or to comment on any other matter.*

Tables and *Figures* are **ordered logically** and **numbered sequentially** — **[YES]** / [NO]

Tables and *Figures* have **captions that explain** all their major features — [YES] / **[NO]**

Tables and *Figures* have **captions that complement** the information in the main text — **[YES]** / [NO]

Tables and *Figures* present data that **relate** to the study objective — **[YES]** / [NO]

Tables and *Figures* present data that are **consistent** with and support the description of results — [YES] / [**NO]**

Tables and *Figures* have **succinct and informative titles — [YES]** / [NO]

Figures are **accessible** (elements are clearly labelled, accessible colour palettes, colour contrasts, font size legible, etc.…) — [YES] / **[NO]**
Please, check our [Figure guidelines]

Figures with **maps or cross-sections** contain all **elements to be understood** (north arrow orientation, scale, visible coordinates, sufficient coordinate grid intercepts) — [YES] / [**NO]**

Figures with **maps** have **sufficient location information** (in the map or caption) — [YES] / **[NO]**

Cross-sections have clear labels for **scale and coordinates** at ends and within-section kinks — [YES] / [NO]

All georeferenced elements are provided in common format (.shp, .geotiff, .kml) [in an open-access repository] — **[YES**] / [NO]

Citations throughout are relevant, suitable, and comprehensive — **[YES**] / [NO]

Comments:

Some scale bars and legends are missing. Coordinates are limited or not present on several figures. There are data in the tables that are not explained or discussed in the captions or main text. Some of the figures are quite small and difficult to see. See annotated manuscript for details.

B6.2) Author's responses

Figures have been improved based on the annotated comments (scalebars, symbols, legends, captions and coordinates).

All data in tables is now explained in methods section according to the requests in the annotated comments.

Section C: Additional comments

C1) Minor/line-numbered comments

C1.1) Reviewer's comments

See attached annotated manuscript with my line-by-line comments.

Introduction

Line 56: You recognized strain or deformation, not stress. You can hypothesize what paleostress caused the strain.

Rephrased accordingly

Line 63: Rapakivi needs to be defined. It is not common knowledge to anyone outside of igneous petrology.

Specified and inserted reference

Line 70: This section might be not be necessary as it is mostly describing the methods.

This section was removed

Line 74: Could change to “to guide”

This paragraph got removed

Line 78: There are studies that show paleostress inversions based on brittle fault planes only relate to local strain, and not regional stress. See Riller et al., 2017 “Fault-slip inversions: Their importance in terms of strain heterogeneity, and kinematics of brittle deformation”.

See response to 1.2

Line 84 (Figure 1): This figure is quite good. The trace of the Scandinavian coastline is a good addition and could maybe be bolder, or it could have a light grey colour to make clearer?

Figure 3 location is Fig 3a, b, or c?

Increased line width for the coastline. Added specification regarding location of Fig 3a and Fig 3b-c. Added coordinates.

Geological background

Line 93: This section is quite long and reads in a complicated way, making it hard to understand. The text could be shortened and a figure such as a stratigraphic chart could be used to show the relationships between the described geologic units. Additionally, details that are not pertinent to this study’s results could be removed.

The section was shortened and generalised for better readability. Age information regarding geological units (Caledonian, Sveconorwegian and Proterozoic) were added to Figure 1, we believe a separate stratigraphic chart is not required.

Line 99: Pretty long sentence, maybe break up into two?

Deleted details of the sentence that are not important to this study.

Line 122: Bothnian Bay isn’t shown on Fig 1

Bothnian bay added.

Line 184: What does this mean? This term should be explained. As its so deformed it can’t be deformed more?

Yes, correct. For clarity added the explanation: “(bedrock became fragmented by brittle structures to a point which hindered the formation of new brittle structures)”. We also touched on this at the beginning of the introduction.

Line 191: How does this support the current erosional level hypothesis?

Clastic dykes must have been filled by sedimentary material relatively close to the erosional surface. Since we now observe them at the erosional surface we can assume the erosional surface is close to where it was when the dykes were filled.

Methods and data

Line 227: What do these measure? Conductivity?

Added a reference to Nordbäck et al. 2023 where this is explained in more detail: “Since brittle structures increase the porosity and permeability of crystalline rocks, they are typically associated with hydrothermal processes, which in turn increase or decrease the magnetic susceptibility of the bedrock and lead to positive or negative magnetic anomalies along brittle deformation zones. Also, the low temperature weathering of fractured rock decreases the magnetic susceptibility. Furthermore, the presence of sedimentary infill and the contained groundwater within the topographic depressions above brittle deformation zones lowers the magnetic field and increases the electrical conductivity.”

Line 265 (Figure 2):

Legend for bathymetry in (a) says m.a.s.l (meters above sea level). Should this be meters below sea level? Or is this land and the areas with the lineaments are just the outcrop areas?

The inset in and details in (a) are hard to see.

The legend is for the elevation of the LIDAR DEM and is thus meters above sea level. The details in the inset were improved for better visibility. Yes, the details in Fig 3a are hard to see which is why we have included the zoom ins in Fig 2b-c, in this way we think both the extent (Fig 2a) and the detail (Fig 2b-c) of the orthomosaics and fracture trace dataset becomes visualized. Coordinates added to Fig 2a.

Line 311: The undeformed rock may be isotropic, but once it is deformed this assumption does not hold true. Thus some studies show that fault slip data is not a good proxy for paleostress (e.g., Riller et al., 2017).

See response to 1.2

Line 312: Aren't these rocks over 1.5 Ga and the supposed deformation between 1.5 and 1.2 Ga? Given the uncertainty on age dates and tectonic history of this time there is plently of time (300 million years) for deformation to accrue and provide mechanical anisotropies. In addition, the study is of fault zones, which are anisotropic by definition irregardless of how old they are. This assumption needs more explanation.

Yes, the rapakivi we have studied is 1.58 Ga. Due to the anorogenic character, the rock lacks any ductile deformation structures. Now rephrased this part to emphasise the absence of ductile anisotropies more and brittle less. We think that it is reasonable to assume that at least the first set of faults would have been formed in relatively isotropic material. The uncertainties are now also discussed in more detail at the start of the discussion.

Line 344: En echelon tension fractures can rotate during subsequent fault slip often forming a sigmoidal shape. How was this dealt with?

The fractures we have mapped are typically quite planar features. Added the following description: "Strongly sigmoidal en echelon fractures were not observed within the Åland rapakivi, which indicates that no significant rotation of stress or fractures occurred during shearing. When slight curvature towards the tips of en echelon fractures was observed however, we measured the orientation of the planar part of such fractures."

Results

Line 425 (Figure 3): Bathymetry needs a scale with actual depths.

The scale was provided with depth information.

Line 431: Specify which color of line represents this data.

Specified colour as light blue in caption.

Line 464: Chapters?

Deleted this sentence as unnecessary.

Line 474: An example of a paragraph that can be shortened to be one sentence. "Although cross-cutting relationships were rarely visible, in Geta subregion 5 one cross-cutting relation demonstrates an E-W trending faults predates a ENE-WSW trending one.

Shortened accordingly.

Line 476: about

The correct term should be abut but this got removed.

Line 496: This structure looks dextral?

The order of the a, b and c captions were wrong, now corrected.

Line 498: This isn't indicated on the figure

The order of the a, b and c captions were wrong, now corrected.

Line 499: visualized

Corrected

Line 500: visualized

Corrected

Line 505: Were there no other reasons to define them. For example by defining them spatially, based on different lithologies, different faulting styles, or orientation?

The lithology is rapakivi for the entire area we have investigated, as mentioned in 3.3 there is only some gradual compositional and textural variation. Observable faulting styles are also similar at all locations we have visited, consisting of shear fractures or small fault zones. As can be seen in Figure 8 the fault orientations are also repeating themselves. Added a short explanation here.

Line 510: Edit to make it sound not like a thesis.

Modified.

Line 515 (Figure 6): The fonts describing the stereonets needs to be larger.

The the dextral and sinistral symbols could be smaller as to not cover the figure up so much.

Fonts were enlarged. Symbols were shrunk.

Line 516: Needs some more detail on the stereonets. E.g. Lower hemisphere stereonet projections at bottom left show… Stereonet at top right shows….

Details were added.

Line 532 (Figure 7): Stereonet data is hard to see. The pole symbols could be larger. What do the contours represent? The contours should also have an associated legend.

Pole symbol size was increased. Legend added to contours.

Line 539: Are there any other data that confirms that these are independent populations of faults. For example, cross-cutting relations, wallrock, or fault orientations. Added the following description to chapter 3.3 regarding paleostress analysis: "The studied fault structures within the Åland rapakivi are of varying orientation and kinematics but similar regarding fracture type, morphology, and mineral filling. Regarding mineral fillings, there is also a general difficulty to observe fillings or thin coatings from eroded bedrock outcrops. Thereby, field classification into separate fault families could only be performed based on the orientation and kinematics of the faults."

Line 550: Waste?... Maybe scatter is a more appropriate classification.

Changed into scatter

Line 551: This is very interesting.

Yes, and it could also be seen as supporting that the deformation occurred in relatively isotropic material (at least in the outcrop scales). The deviating orientation of the long lineaments could then be explained by localisation and reactivation of large-scale anisotropies of the Svecofennian bedrock that surrounds the Åland batholithe.

Line 571: New paragraph

Changed accordingly

Line 584: Are these orientations compatible with each other? Maybe they represent a different event? If not, mention that this was tested?

They are not compatible, in this scatter the remaining observations no longer form any compatible and reasonable paleostress states (at least 4 observations are required for a sub-set). Within the text of 4.4.1 we describe that: "The remaining observations that were omitted from both these sub-sets were assigned to "scatter", as these could not be further processed into other mechanically reasonable sub-sets and paleostress states (Figure 8d)."

Line 601: Why isn't this mentioned in the text?

Good point. Added to 3.3: "The Wintensor software also estimates the quality of the results from A to E, which is based on factors such as number of data, slip deviation, slip sense confidence for individual faults, and type of data (Delvaux & Sperner, 2003)." Added to 4.4.1: "Due to the generally low amount of slickenside observations, and low number of fault observations within some of the sub-sets, the quality of calculated stress tensors is typically of intermediate (C) class, however, lower quality (D–E) results were also attained for some of the sub-sets (Table 1)."

Line 633: What does this mean?

Good point, this was not explained. Now added information to chapter 3.3: "GArcmB estimates both the orientation of principal stress axes and stress ratio (R) for each joint set based on the Bingham concentration parameters K1 and K2 (Bingham, 1974; Yamaji et al., 2010). The spread of orientations from the minimum to maximum concentration axes is described by K1 and from the maximum to intermediate by K2. For circular distributions the value of K1 = K2, for elliptical ones K1 < K2 and for girdle distributions K1 ≪ K2."

Discussion

Line 651: It is not unusual for stress tensors to rotate over short distances, so this not necessarily an uncertainty.

Reformulated this part and removed the uncertainty part, also managed to condense the text.

Line 665: This could use some more explanation and a citation.

Opted to add just a citation to hold down the length of the text.

Line 666: Could rename these Set A and Set B to ensure the reader doesn't not mistakenly correlate them with Set 1 and 2 of the faults.

Agree. Sets renamed accordingly.

Line 681: Wouldn't exhumation reduce vertical stress? Could these joints instead be explained by burial?

In theory burial is a possible cause too (Mesoproterozoic sedimentation), but if we consider that in general the bedrock experienced multiple kilometers of exhumation between rapakivi magmatism and Cambrian times, this could well provide the needed decrease in temperature and/or increase in extensional horizontal strain for tensile failure to occur. Also according to English (2012) it is more likely for exhumation to cause tensile failure compared to burial. The Nadan & Engelder (2009) study from intracontinental granitoids is a good analogue that would fit our observations: thermoelastic relaxation and isobaric cooling during the exhumation of intracontinental granitoids causes development early vertical microcracks, interchanges between σ2 and σ3, and late horizontal cracks. Added citation and this information as a basis for our interpretation.

Line 683: But some of the Set 2 joints are filled with clastic sediment… this would suggest that they also formed at higher crustal levels?

The clastic material only gives us a minimum age for the joints. We believe they were formed earlier and at some depth within the crust and only filled once exhumed close to the surface. According to Friese et al. (2011) they were also reactivated and dilated due to Cambrian tectonic stresses.

Line 732: Hydrothermal fluids don't have to be associated with the granites necessarily. They can just be the result of a meteoric fluid circulation to depths with high temperatures. Yes, but if we consider the crystallisation temperature of e.g. greisen and quartz, the hydrothermal gradient, the depth where the hydrothermal alteration occurred we will be needing an external heat source.

Line 757: This is a great figure to explain the interpretations.

At normal zoom the fonts are probably too small.

Increased the size of fonts slightly.

Line 766: This section is very hard to follow and understand. Suggest some rewording. Importantly, it is hard to determine which, and how, the results relate to these interpretations.

This section was clarified by changing some of the wording, by adding more references to figures and by adding geodynamic maps to Figure 12 (representing different Mesoproterozoic tectonic stages, as requested by reviewer C).

Line 770: The ones in the Geta outcrops or the other ones? The Geta outcrops are within the batholith? so this is confusing. Suggest some rewording.

Reworded and used the term lineaments to make things easier to follow here.

Line 812: E-W structures in bathymetry?

Here we refer to the reactivation of the LSGM zone (Figure 1) that has been associated by Nironen (1997) to the 1.64 Ga rapakivi magmatism. Added reference to LSGM (Figure 1).

Line 817: Be more specific on which structures. The ones in bathymetry? Maybe can call a figure here.

Added reference to Figure 12d.

Line 813: If compression is E—W, why are the low angle thrust faults trending E—W as opposed to N—S?

Added information regarding the spread of results by Mattila and Viola (2014). Mattila and Viola (2014) also discussed that the variation in the resolved compression direction can be due to mechanical anisotropy of the shield which also was saturated with fractures and faults. The isotopic data of the low-angle faults indicate Sveconorwegian age (Nordbäck, 2022). The ENE-WSW trending faults visible in Figure 12b are also subparallel with lithological contacts and ductile structures in Olkiluoto which likely influenced their localisation.

Comments by reviewer C and Authors' reply

I think the article entitled "Mesoproterozoic strike-slip faulting within the Åland rapakivi batholith, southwestern Finland" can be published after revisions and authors response to the following questions:

1. I suggest authors provide more detailed formulas and math behind stress analysis in the method and data section, it will help better clear the methods for readers. Authors can use this paper: Ezati M, Gholami E, Mousavi SM (2020) Paleostress regime reconstruction based on brittle structures analysis in the Shekarab Mountain, Eastern Iran. Arab J Geosci 13:1232.

   Since we are requested by reviewer B to condense and shorten the length of the paper, we address the mathematical basis for calculating principal stress tensors from fault data by adding references to to Angelier (1979, 1984), Zalohar and Vrabec (2007) and Ezati et al. (2020).

   Regarding the calculation of principal stress tensors from joint data this section was also extended regarding the concentration parameters K_1 and K_2.

2. Can author explain why these stages of evolution in stress regimes has happened and what has been behind such stress change?

   The available literature does not provide us any suitable explanation for the cause of our proposed Mesoproterozoic compression and strike-slip regimes at stages 1 and 2. Current models attribute the Åland region to stable/rifting conditions during Mesoproterozoic times, while the impact of accretionary and collisional orogenies in western and southern parts of Fennoscandia did not affect this region. Thus, at this point, we are not able to give confident answers to this question but based on our results there was more complexity involved than previously thought.

   Added to 5.3: "Compared to previous models describing stable/extensional conditions for the Mesoproterozoic within central Fennoscandia (e.g., Bingen et al., 2008; Bogdanova et al., 2008), our study finds evidence of a potentially more complex evolution involving a switch from extension to compression between 1.55–1.4 Ga (Stage 1). The cause for such a change in tectonics is currently unknown, but it is tempting to speculate on a possible link between a change to strike-slip during Stage 1 and the failed rifting beneath the Bothnian basin."

3. I suggest authors can add a series of tectonic and geodynamic model map combining with reconstruction the paleo-stress fields of the studied area during different geological times.

   A series of tectonic and geodynamic model maps were added to Figure 12.

4. There is a general question that should be discussed more thoroughly in the paper. This is a problem problem of age of faulting that arises in all the faulted areas where the paleostress techniques are applied. The problem is that each new tectonic stage can produce faulting or re-activation of faults in older units. The basic criticism that faults observed in for example Mesoproterozoic formations to not indicate that these faults were active in Mesoproterozoic times. They could be of much younger age. By starting with faults in the youngest formations you can be sure that these did not form at an earlier time. But then proceeding back in time how can you eliminate the youngest faults in older terrains? Is it by their orientation in space? The authors do not present compelling evidence how this problem is solved. For answering this question authors can use this paper: Ezati M, Rashidi A, Gholami E, Mousavi S.M, Nemati M, Shafieibafti Sh, Derakhshani R (2022) Paleostress Analysis in the Northern Birjand, East of Iran: Insights from Inversion of Fault-Slip Data, minerals 12:1606.

   Yes, old structures in Paleoproterozoic rocks being reactivated and overprinted by Mesoproterozoic and Neoproterozoic events has also been observed in e.g., Viola et al. 2013, Mattila & Viola, 2014 and Nordbäck et al., 2022.

Since previous brittle structural studies from Finland are almost exclusively dealing with Paleoproterozoic rocks, our intention here was to better investigate the potential Mesoproterozoic brittle development by studying the “relatively young” Mesoproterozoic rapakivi. We thus “eliminate” the Paleoproterozoic development which by itself was very long and complex within Fennoscandia. As can be seen in Figure 1, the Mesoproterozoic rapakivi granites belongs to some of the youngest exposed lithological units in central Fennoscandia. Unfortunately, a large portion of the even younger units, such as the sedimentary successions are beneath water and are thus difficult to study.

We think that the presented structural data can be used to tentatively constrain the minimum age of faulting stages 1 and 2 as Mesoproterozoic (see. 5.2). In future, we plan to conduct e.g. isotopic dating of fault gouges which we believe is still needed for confirming our structural interpretations of the current paper. If possibilities arise in acquiring brittle data from e.g. the offshore sedimentary areas we will definitely be very interested to see if more details of the Neoproterozoic and younger tectonic evolution can be unravelled.

In addition, we also believe one advantage of our data is that since it consists largely of shear planes and associated tensional fractures (i.e. en echelon) it can quite confidently be interpreted as representing the initial stage of fault nucleation. Thus, the investigated structures are not associated with as much uncertainty regarding nucleation vs. reactivation as e.g., slickenside observations from fault zones associated with more strain where evidence of the first slip event may have become erased by later reactivations such as is the case in Paleoproterozoic rocks of Fennoscandia.

Comments by associate editor and Authors’ reply

The manuscript entitled “Mesoproterozoic strike-slip faulting within the Åland rapakivi batholith, southwestern Finland” which you submitted to Tektonika has now been referred.

The manuscript provides an interesting reconstruction of brittle tectonic evolution between ~1.55 and 1.2 Ga in the Åland rapakivi granite batholith in southwestern Finland and provides an example on this type of use of structural data at several different scales.

You presented a large and high-quality data set and built a tectonic evolution of the region that appears reasonable and fit the geodynamic context.

Both the Reviewers acknowledge these positive aspects and agree that the manuscript deserve publication after revisions.

In particular, according to Reviewer1, the text could be edited to be more succinct and easier to read, especially with regard to the "Geological background" and the final section of the discussion sections (5.3).

Most of the pertinent features described in the text are illustrated with comprehensible photos and figures. However, according to Reviewer1, some of them needs improvements (please refer to comments of the Reviewers) and Reviewer2 suggested to add a series of tectonic and geodynamic model map combining with reconstruction the paleo-stress fields of the studied area during different geological times.

Regarding the interpretation of the fault-slip data, both Reviewers identified some points that need to be addressed/discussed. In particular:

1) the use of fault kinematic as a paleostress vs paleostrain indicator and the assumption of isotropic medium (Reviewer1)

2) the math behind the stress analysis (Reviewer2)

3) the age of faulting and the re-activation of older faults (Reviewer2).

I personally would also suggest to clarify how the data are sorted in sub-sets (paragraph 4.4.1, lines 479-480): is it this the result of an inversion done by the software on the full dataset or is it based on observed field features (cross-cutting relationships, mineralizations, etc.)?

This comment is associated to the annotated comment of reviewer B line 539.

To reinforce conclusions and broaden the potential impacts of the paper the suggestion of Reviewer2 to clarify the reasons of the changes in the stress regime should be addressed. This also would help to fit your results into the geodynamic scenario also to the readers not familiar with the specific regional geology.

The changes made to section 5.3 address this issue.

As final recommendation, tabulated structural data should be provided in the supplementary data, as suggested by Reviewer1.

Tabulated structural data is now provided.

Acceptance letter

Dear Dr. Nordbäck,

We are delighted to accept your manuscript for publication in Tektonika. As you will see, Laura Federico as AE has assessed you have addressed all reviewer comments. Laura does highlight two minor points, which can be addressed I think during the proofing stage.

Kind regards,

Craig Magee

------ AE Letter

Dear Dr. Nordbäck,

thank you for revising your manuscript “Mesoproterozoic strike-slip faulting within the Åland rapakivi batholith, southwestern Finland” effectively, in line with the comments, questions and suggestions of the two reviewers.

From my side I see the paper significantly improved in terms of readability and internal organization and therefore suggest to accept your revised manuscript for publication in Tektonika.

I have only two minor suggestions:

1) when adding the coordinates to the figures 1, 2 and 3, the coordinate grid should be tighter (I mean, with at least two coordinates ticks on each side);

2) in the new caption of Fig. 12 (line 1005 of the revised manuscript) “C-d” should be “C-f” instead.

Thank you for submitting your significant work Tektonika.

With kind regards and best wishes,

Laura Federico