REVIEW RESPONSES TO MANUSCRIPT VERSION 2

Please find our revised manuscript titled "***Insights into the tectonic evolution of the Svecofennian orogeny based on in situ Lu-Hf dating of garnet and apatite from Olkiluoto, SW Finland***" that we submit for consideration to be published in the Solid Earth.

Below you also find comments to the review.

Sincerely on behalf of all authors,

Jon Engström

Reviewer #3

Insights into the tectonic evolution of the Svecofennian orogeny based on *in situ* Lu-Hf dating of garnet and apatite from Olkiluoto, SW Finland
by
JON ENGSTRÖM, KATHRYN CUTTS, STIJN GLORIE, ESA HEILIMO, ESTER M. JOLIS AND RADOSLAW M. MICHALLIK

General
This manuscript has been previously reviewed by two experts and I have had an opportunity to see their assessments. Therefore, I have tried not to repeat their comments. However, because I agree with the notion of Reviewer 2# that the samples and their analytical results should be treated separately, I added my views to the same topic. While reading, I also made some small formal comments on language etc., they can be skipped if inappropriate.
The main topic here is dating of different phases of metamorphism by in-situ Lu-Hf method on garnet and apatite. The latter was also dated by U-Pb method. This method is quite novel and therefore, as far as I understand, still in initial stage. Therefore, the results may contain shortcomings that are not yet fully understood. By this I mean e.g., the very large errors the method yields. Or maybe the instruments used are not yet sensitive enough for high resolution.
The garnet dating from leucosome and mesosome failed to decipher the two metamorphic events that were previously dated by U-Pb method from zircons in leucosomes. All the garnet analyses combined gave a "pooled" age of 1834 ± 17 Ma. Meaningfulness of such approach can be questioned. This is further discussed below in detailed comments. Despite this quite critical review, I see this method promising and at this stage even the difficult cases are good to publish for the use of future developments.
The apatite was dated by in-situ Lu-Hf and U-Pb. These data are highly welcome to regional metamorphic studies as they are rarely used in this part of the Precambrian world.

Dear reviewer,

We appreciate all additional comments to the manuscript that improved this second version of the manuscript. We acknowledge especially the comments on the Lu-Hf method and thus we have been additionally modified the text according to the comments. Since the small garnets (MM30), have low Lu content for the garnets that we sampled, we decided to not "pool" the age and thus in the final discussion of the results we use mainly the large garnets (MM31) Lu-Hf ages.

The response to the detailed comments is answered and found below with red text next to the comment.

Detailed comments

line 26-30: repetitive use of the word "polymetamorphism"

This has been accordingly adjusted.

31-34: There is a bold statement arguing that Lu-Hf garnet method represents the metamorphic age of the rock better than the U-Pb monazite or zircon. This can be questioned. Lu-Hf garnet is still quite a new and incompletely understood method which so far gives quite large errors. U-Pb zircon in leucosome is a widely used and well-known method to date peak metamorphism (it is assumed that melting is coeval with peak metamorphism and zircons crystallise in the melt, hence the connection) with high precision. Monazite is another story…

This statement has been re-written and modified that is a new method that is a good complement to older methods of age determination, such as U-Pb zircon dating.

38-39: It is stated that "at least one, possibly two, significant metamorphic events". According to previous investigations, it is quite convincingly shown that there are at least two metamorphic events in the region. I will come back to this this later while commenting Chapter 5.1.

This has been modified and defined now from the previous studies that two events occurred.

83-84: Yes, crustal thickening took place, but neither of the cited articles argued that it caused the peak metamorphism and melting. Instead, Mäkitie et al. stated that the heat source is unknown and Chopin et al. said that the melting is related to channel flow.

This has been accordingly modified.

90-92: Transpressional: Ehlers et al. 1993 (Precambrian Res.) were the first to describe the transpressional tectonics in this part of the world; should be cited.

This citation has been added.

102. No good to start a chapter with a reference. Change the word order.

This has been accordingly modified.

123-125. About the two metamorphic events, see comment line 390.

This has been accordingly modified.

137: "This study includes whole rock geochemistry of the different lithological units". See my comment on line 272.

The motivation to add this geochemistry part to the manuscript has been added.

138-139: "in the first metamorphic phase in Olkiluoto (Engström et al., 2022)". Because these two phases are repeatedly mentioned, it could be appropriate to call them, e.g., the first metamorphism (M1, older) and the second (M2, younger).

This has been accordingly modified.

145-146: In this ms. a migmatitic rock is divided into the leucosome and matrix. In the common migmatite terminology these are called the leucosome and mesosome.

This is a valid terminology change and has now been implemented in the whole document.

158-160: In this sample description it clear that different types of garnets occur in the mesosome vs. leucosome. See later comment.

Yes, that was the aim of the sampling and hopefully now better described.

180: Chapter 3.3. These analytical methods are already published in the cited report which is openly available online.
Yes, but an earlier revision asked for this, so we have short recap about that.

188: Do you mean "The second largest" ?? or maybe "Another large garnet" ??
This has been changed accordingly, it is another large garnet from the same leucosome that has been used.

272: Chapter 4.1. The whole chapter is a little bit strange for several reasons. The authors do not have own data but refer to the data in Kärki & Paulamäki (2006) report, which is already published and available online. The data tables are not in the report, so this maybe is what the authors mean in the Acknowledgements by expressing their gratitude to Posiva Oy for access to the data. Here the authors only use some major elements and show the TAS and AFM diagrams. The TAS diagram was also shown in the original report (but not the AFM diagram). These data are not used in the later discussion. The data seem to have no value for the topic of this ms., at least it is not described.
This reason to include this part in the manuscript is to describe the chemistry of the TGG rock type in Olkiluoto and thus have a more regional coupling to the rocks outside Olkiluoto. This reasoning is also coupled now more to section 5.2.

276: …then…?
This has been accordingly modified.

324: Chapter 4.3. These garnet ages are the core of the ms. I will come back to these later in Discussion.
This is explained later in the discussion.

328: …the age calculations…
This has been accordingly modified.

328-229: …When all the data are plotted…
This has been accordingly modified.

332 and 334: Give the MSWDs also for the core and rim ages. I explain later why on line 390.
These were included in the supplementary figures referenced in the text but have now also been added here.

334: not identical age, just overlapping within errors.
The core age is 1828 ± 11 Ma and the rim age is 1828 ± 21 Ma – this is an identical isochron age but with a larger uncertainty so no change has been made here.

341: "Given the overlap in uncertainty, the proximity and similarity of the samples," This sentence can be removed, these are already described earlier and complicate the sentence, when it continues with "if"
This has been accordingly modified.

342: …data are…
This has been accordingly modified.

347: (…MSWD = 1.5). According to Fig. 9A it is 1.6
This has been corrected.

348-349: These ages are not identical, just overlapping within errors.

This has been accordingly modified.

353: …isochron age -> lower intercept age
This has been accordingly modified.

390: Chapter 5.1. In this chapter the age determinations are discussed. In the earlier paper from the same locality (Engström et al. 2022), the metamorphism was dated by U-Pb zircons from two leucosomes in the migmatitic metapelites as 1858 ± 7 Ma and 1851 ± 8 Ma. As no younger zircons were found, the leucosome must have been related to the first melting episode, M1 (cf. Saukko et al. 2020). The second metamorphism M2 in Engström et al. (2022) was less precisely defined at 1.82-1.78 Ga. Just a few kilometres S of Olkiluoto in Rauma, Vehkamäki et al. (2021, Inst. Seism., Univ.Helsinki, Rep. S-71) dated zircons of two populations from the leucosome in a migmatitic metapelite; 1.86 and 1.83 Ga. Towards the W in central Sweden Högdahl et al. (2012) also dated two metamorphic events at 1.87-1.86 Ga and 1.82-1.80 Ga. The younger M2 is ubiquitous in southern Finland and central Sweden, described in numerous studies. It is the older M1 that has only lately emerged from behind the strong M2 overprint.
On the basis of the previous age determinations reviewed above, it is very likely that these events also prevailed in Olkiluoto, as proposed by Engström et al. (2022). In the present study, the authors have dated two types of garnets; small garnets in the mesosome and large garnets in the leucosome. In the sample description and also later it is speculated whether the garnets are of different generations. In fact, the face value age (without error) for the small garnets is 1857 Ma and 1829 Ma for the big garnet, which is further divided into 1828 (±11) Ma for the core and 1829 (±21) Ma for the rim domains. It is a pity that the MSWDs for these analyses were not shown, but I guess is that the core age has the lower one. Looking at these ages without errors, they are exactly what might be expected for the M1 and M2. Now the problem is the very large errors in the ages. To solve this the authors chose to use a pooled age of all the analyses to get smaller errors (result 1834 ± 17 Ma). This is a highly questionable way to use the data. It seems that the sampling was not structurally controlled to separate possible different garnet generations. To the S of Olkiluoto in the Turku area, two generation of garnets were described, the first elongated syn-D2 garnet was deformed in D3 which in turn was coeval with leucosome containing large garnets (Väisänen & Hölttä 1999; Fig. 14g). This might be the case in Olkiluoto, too. But the major problem here is not the sampling, but the resolution of the Lu-Hf garnet method, which is incapable of solving so detailed a problem.
You are spot on – Lu-Hf for these samples is not high enough resolution to split the older and younger events. You are also right that this is a quite new and not completely understood method (line 31 comment above). I have included the MSWDs as you suggested but the core MSWD is slightly higher than the rim. The reason for this is that MSWD evaluates the fit of the line to the data, the core data has a larger spread so it is more difficult to fit but results in a more well defined age (lower error). The rim data and the small garnet data have less spread in Lu/Hf ratios so the data is easy to fit a line to (low MSWD) but the age is more poorly defined (bigger error).

392: …all the analyses…
This has been accordingly modified.

394: …, then…
This has been accordingly modified.

396: these ages are not identical, just overlapping within error
This has been accordingly modified.

409: …the(se) data form…
This has been accordingly modified.

417: …in the U-Pb and…
This has been accordingly modified.

426: …The zircon U-Pb…
This has been accordingly modified.

475: Fig. 11. Why is the Turku granulite area skipped from the examples in Figure. It is anyway isotopically and metamorphically well-studied migmatite area close to Olkiluoto.
This reference, Väisänen & Hölttä 1999, has been added to the map thus also more constrains on P-T conditions in the Uusimaa belt.

499: …in the Häme Belt…
This has been accordingly modified.

509: "reaching slightly deeper crustal depth than the Häme Belt" ? what does this mean?
This statement has been re-written and modified, so that it infers deeper metamorphic depth.

512: …the Uusimaa Belt…
This has been accordingly modified.

513: …the anatectic melts (or melting)
This has been accordingly modified.

514-515: "indicates that the whole southern Finland domain was subjected to a long hot orogenic evolution with several crustal-scale melt pulses". Chardon et al. 2009. Tectonophysics 477, describes this nicely, worth citing
This reference has been added.

517: Chapter 5.3. This chapter shortly summarises the present knowledge of the chapter title, focusing on the shear zones, but it hard to understand how this literature review is connected to the data in the ms., garnet and apatite age determinations.
The coupling to the manuscript and reasoning to include this now re-written and information added so that this can be defined and tracked better.

519 and 521: back-arc vs backarc … Be consistent with writing style
This has been accordingly modified.

528: Additionally, additionally what? unclear
This statement has been re-written and modified.

531: …show that…
This has been accordingly modified.

574: "similarities between the Olkiluoto site and Häme Belt, and the differences to Uusimaa Belt." What actually are the real differences between the Häme and Uusimaa belts? So big that they are part of the main conclusions? This topic is not clearly discussed in the ms. There are evidently differences in erosion levels, but what else? If this refers to the metamorphic ages, two metamorphic events are found also in the Uusimaa Belt, 1.86 and 1.83 Ga (Väisänen et al. 2021, Inst.Seism., Univ Helsinki, Rep. S-71). The protolith ages are also the same, 1.86 Ga.

This part has been modified and main statement is that more studies is need in this region to better constrain the metamorphic history both for the Häme Belt and the Uusimaa Belt.

623: References: Many references occur twice in the list, e.g., Lahtinen et al. 2005, and many others. Delete the extra.

This has been fixed!

624: page numbers missing

This has been fixed!

714: page numbers missing. Check all the similar references

This has been fixed!

796: Pitkälä…This is an unpublished MSc thesis. A published document should be used: Pitkälä et al. 2018. Inst.Seism., Univ Helsinki, Rep. S-67.

This has been fixed!