Comment on egusphere-2022-1475, RC2

Manuscript Title
Structural framework and timing of the Pahtohavare Cu ± Au deposits, Kiruna mining district, Sweden

Referee's comments in black
Author comments in red

General comments

The subject of manuscript is interesting and potentially of wide audience.

However, in the present form the manuscript is not suitable for publication for the following reasons:

- the text is difficult to understand, and some sections are very confusing;

> We have rewritten the results section 4.1 and discussion section 5.1 to improve the presentation of the data and interpretations. We have also added more information to the background sections to improve the description of the area and structures.

- tectonic structures are poorly described. In particular faults and shear zones are not adequately described;

> Thank you for this comment. We have rewritten the results section to describe the faults and shear zones more clearly. Furthermore, we have added more information to the background sections about the known structures from the region and locally.

- the interpretation of the stereonets (fig 3A-C) does not seem exact; It should be revised and discussed in more detail, (see comments in the annotated text, figure 3);

> We have added more detail to the presentation of the data in the stereonets, including adding additional subfigures to Fig. 3 (now Fig. 4). We have rewritten the text to provide more detail in both the results and the discussion sections.

- some structural terms are cited inappropriately or not proven (e.g. mylonitic);

> We have accounted for your specific comments in text and modified Fig. 4 (now Fig. 5) to better illustrate the structural features.

- a clear and exhaustive description of relationships between mineralizations and stuctures is completely lacking;

> We have added more information to the background section including a new paragraph that describes the structural relationship to the Pahtohavare mineralization in more detail. Additionally, co-author O. Martinsson has provided a new mine level map from the Southern Pahtohavare deposit and a surface map showing the ore location with additional structural data at the Southeastern Pahtohavare deposit (Fig. 6, new manuscript). This work has not previously been published but adds significantly to the manuscript by illustrating the structural relationship to the ores. The new surface structural measurements from Southeastern open pit have been added to the stereoplots in Fig. 3 (now Fig. 4C-E).

- several statements in the “Discussion section” seem speculative;

In general, we disagree that our statements are speculative in the discussion section as the interpretations are supported by several previous studies (see specific comments below). However, we have rephrased our text to improve clarity, and hope that rewritten sections of the results and discussion sections help the reader verify the interpretations made.

- some figures (Figure 1 - 3) are poorly mentioned in the text and some localities and/or mineralizations are not reported in these figures;

We modified the text to include more figure referencing to aid the reader. Thank you for this comment.

- the photos in figure 4 illustrating the meso and microstructures are of very low quality. This makes comparison with the text very difficult.

Thank you for this comment. We have modified the figure (now Fig. 5) to improve the resolution of the photos and to illustrate the structures described in the text more clearly. Some figures have been removed due to low quality or lack of relevancy.

Specific comments

Given the subject of the manuscript (structures and mineralization), I suggest that the authors review the organization of the text in the following way and order:

1) detailed description of the tectonic structures (foliations, faults, fractures) at the meso and microscale. Interpretation of structural data should be revised, in particular as regard relations between bedding and cleavage;

Thank you for your comment. We have revised the manuscript to add more detail about the meso- and micro-scale structures that provides more coherency to the interpretations in the discussion section.

2) detailed description of the mineralizations (mineralogical association, host rocks, style of deposit, type of veins, deformation) with high quality meso and microphotos;

We have added detailed descriptions of the mineralization at Pahtohavare to the background section, as well as a new mine level map for Southern Pahtohavare and an open pit map for the Southeastern deposit to improve the description and visualization. A full deposit description as a part of the results section is beyond the scope of this study, however more details and photos can be found in Martinsson (1997).

3) exhaustive description of the geometric and spatial relationships between mineralizations and tectonic structures;

Material has been provided by O. Martinsson (new mine level map from Southern Pahtohavare and open pit map from Southeastern Pahtohavare) to support the

description of the geometric and spatial relationships between the mineralization and tectonic structures.

4) the “Discussion section” should be re-organized on the basis of these data.

Thank you for these comments. We have rewritten and reorganized the results and discussions sections to improve the coherency and organization.

This order of presentation of analytical data would allows

(i) the authors a better formulation of the "Discussion section" and

(ii) a clear understanding for the reader

Other comments and technical correction are reported in the annotated text.

Comments on Introduction

Line 57: "very low grade"? "low grade"? explain
Upon rewriting the introduction, this sentence has been removed. However, details on the metamorphic conditions are given in the background sections 2.1.2 and 2.1.3.

Comments on Background

Line 85-88: deposits? mineralization? explain!

We have added more examples to improve the structure of the paragraph.

Line 91-93: report the "strike of foliation"

This has been edited in the manuscript.

Line 103-104: provide PT conditions

We have added more detail to clarify what is known about the PT conditions associated this metamorphic event.

Line 117-118: Where are these depsits?

We have added the Rektor and Luossavaara deposits to Fig. 2.

Line 121-124: where is this locality?

We have added a description to the text for the Gällivare locality as well as a reference to Fig. 1.

Line 144-146: explain

We have explained the tectonic context of the Matojärvi formation in the new subsection 2.2.2.

Line 149-150: PMS?

The PMS abbreviation stands for Perthite monzanite suite. It is defined further up in the text.

Line 152-155: What age?

The age of the late orogenic intrusion is 1792 ± 4 Ma. It has been added to the text.

Line 156-158: two phases

locality not shown in figure 2

There are actually several phases of deformation. We have expanded this section to describe them.

The Luossavaara deposit has been added to Figure 2.

Line 165-168: what does it mean? explain better

We have expanded in text to try to clarify the nature of the second deformation event.

Kiruna Naimakka deformation zone not reported in figure 2

This has been modified in Figure 2.

As general comment the authors should refer more to the figures, especially figure 2

Thank you for this comment. We have modified the section to refer more to the figures.

Line 175-177: along the NS striking tectonic contact between the Hopukka and Luossavaara formations, with.....

We prefer to keep the original wording because the brecciated character of the hanging wall and footwall zones may not be because of tectonic activity alone.

Line 179-181: give radiometric age

The age of the syn-volcanic faulting has been added to the text.

Line 186-187: what kind of replacement? explain!

The replacement is selective-pervasive magnetite hydrothermal replacement of conglomerate clasts with Cu mineralization.

193-195: give the position in figure 2

Thank you for your comment. We have added the Pahtohavare ore deposit localities to figure 2, as well as figure 3 (now figure 4).

197-198: hydrotherml breccia? Explain

We have expanded the section describing the Pahtohavare deposits.

200-202: based on what evidence?

This is based on a U-Pb TIMS age determination on rutile from a ferro-dolomite-pyrite-chalcopyrite vein near the Rakkurijärvi area which yielded an age of 1859 ± 2 (Martinsson et al., 2016). This has been added to the manuscript.

Comments on Results

As general comment this paragraph is hardly to understand for the poor text organization and illustration (Fig. 4)
Thank you for this comment. We have rewritten the results section to improve the organization and presentation of data.

Line 234: what is the kinematics of the shear zone on the western flank of the fold?

We have restructured the description of the shear zones in the results section. The main information we have is from a scapolite lineation on a foliation plane (80/162) in a small-scale shear zone with the orientation of 55/162. We discuss the kinematics in the discussion section and interpret them to be dominantly reverse with a minor sinistral component.

Line 239: Parasitic folds are coaxial with main fold.
We agree that parasitic folding should follow the overall geometry of the fold, but structural deflections and transposition can cause parasitic fold orientations to vary. We argue that only one parasitic fold measurement does not give the full picture, but unfortunately this outcrop was the only measurable outcrop in the field area. However, the stereoplot from the northern limb (now Fig. 4A) better illustrates the strength of plotting many bedding planes with varying orientations together because the geometry of the fold (visualized in the aeromagnetic anomaly map, now Fig. 3) is maintained.
In my opinion the spatial distribution of bedding poles might be interpreted as evidence of two folding phase.
Check this.
The multi-phase deformation history associated to the Svecokarelian orogeny in Norrbotten records more than one folding event, however previous structural work within the Kiruna area indicates that the district shows one to two fewer folding events than the rest of the region (e.g. Grigull et al., 2018, Andersson et al., 2021). Folding is absent in the earliest deformation event in Kiruna and generally the first phase of folding is recognized associated to the second E-W crustal shortening deformation event. A later N-S oriented gentle refolding in chlorite-white mica domains occurs as well, but typically is rare to observe. While the results of this study indicate an earlier S1 foliation is recorded in the greenstone rocks, our data does not unambiguously reveal an early folding event as well. Without clear field cross-cutting relationships, we prefer not to interpret two fold generations from solely the stereonet data.

Line 241: The authors should describe field relations between bedding and tectonic foliation.

Thank you for this comment. We have added more description to the text.

Line 241: in figures 4B-F mylonitic structures are not evident.
The presence of asymmetric porphyroclasts indicates a prevalent simple shear deformation.
If there is evidence of mylonitic deformation it should be shown clearly.
The evidence of mylonitic deformation in our sample include the following: 1.) S-C shear textures 2.) asymmetric porphyroclasts and 3) porphyroclasts sitting in a finer grained recrystallized matrix. We have added annotations to (now) Fig. 5C, and added another microphotograph (now Fig. 5F) showing the asymmetric porphyroclasts.

Line 244: where?

The foliation trails in the scapolite porphyroblast is in (now) Fig. 5I. We have modified our annotations to make this clearer and have added the locality of the figure to Fig. (now) 4B.

Line 246: Two foliations are not identified in figure 4H.
In the lower part of the image it seems to see a foliated level at the tip of the pencil.
As comment at line 241, if there is evidence of foliations in intrusive rocks it should be shown clearly.
Thank you for your comment. The S2 foliation is indeed the one that is seen at the tip of the pencil, as well as in other places in the rock above that point. We have modified the annotation in the figure to make this more clear. Please see the response to the Figure Comments section (below) for more details on Fig. 4.

Line 248: It is not exact. The poles distribution is not similar.
Cleavage poles are dispersed along a well-defined EW great circle.
The same is not recognizable for the bedding poles
See comment to figure 3
We agree that it is not exact and mention in the text that it is possible that S2 foliation may be present within the data group. However, we prefer not to make arbitrary groupings based on how well the data fits without field evidence. We do not agree that the cleavage poles are dispersed along an EW great circle. The great circle in the stereonet is the calculated best fit great circle which shows a NE-SW orientation for both the cleavage and the bedding data.

Line 255: biotite-scapolite indicate medium-grade metamorphism. The authors previously attributed very low and/or low grade metamorphism. How are these observations reconciled?
The metamorphic grade of the area is upper greenschist facies but can transition to lower amphibolite facies locally. Regionally, biotite and scapolite occur as a metasomatic assemblage from the metamorphism of evaporite sequences, and can occur locally as an alteration assemblage from hydrothermal fluids. There are likely both kinds at Pahtohavare.

Line 255: give illustration!! (of scapolite veins mimicking axial plane parallel cleavage)
We have added a figure (now Fig. 5B) to show the feature we describe in the text.

Line 259: The structural features of S1 foliation are not described.
We have broadened our description of the foliation in the results section and added additional figures to (now) Fig. 5 to better illustrate.

Line 265: These statementes should be reported in the "Discussion section"
This has been edited in the manuscript.

Line 270: what fabric? The same cleavage of Pahtohavare area? Do you have clear evidence of cleavage trasposition?
The fabric reported here is the main foliation seen in the specific outcrops. The foliation is steeply dipping and in the same orientation as the NE-SW shear zone (KNDZ). The main evidence for transposition is that this orientation of foliation only occurs as you approach the deformation zone but is absent in the other parts of the study area. The shear zone can be clearly seen on the aeromagnetic anomaly map (now Fig. 3).

Comments on Discussion

Line 293: "degree" or "type"

We have modified this sentence.

Line 295: "overprinting"? Do the authors mean that the mineralizations precede the deformation, metamorphic and magmatic evolution of the area?
Mineralization formed before, during the early phase, and during the late phase of the Svecokarelian orogeny. Therefore, we mean that there are mineralizing events that can overprint earlier ones. We also mean that deformation, metamorphic, and magmatic events overprint each other and sometimes have similar characteristics. Since deformation, metamorphism, magmatism, and hydrothermal alteration are all ingredients of the bigger mineral system perspective (Wyborn et al., 1994) , we use this sentence to highlight that structural geology can help unravel the events when they overprint each other.

Line 300: What it means?

Energy drives (Knox-Robinsson and Wyborn, 1997) imply the forces that initiate and drive the bigger picture mineral system. They can include deformation, metamorphism, magmatism, and sedimentary compaction. We have modified the text to give a couple examples.

Line 303: Where are these locaties/deposits?
it is difficult for the reader to follow this text without references in the figures
We have added figure references to address this comment.

Line 321: compaction is a diagenetic process
We agree with this statement. A compaction fabric was described occurring in the Orosirian rocks in the central Kiruna area and we argue here that the tectonic fabric S1 observed in the Pahtohavare-Rakkurijärvi area could not have formed from compaction. We have added this information into the discussion section to make the argumentation clearer.

Line 330: These structures are not described and describe and illustrated in the previous text.

We have rewritten our text to better describe these structures and the subsequent interpretations.

Line 334: Hydrofracturing?
Yes. This is possible.

Line 346: This is speculative in the absence of radiometric data

We disagree with this comment. The structural data can clearly constrain the relative timing of the ore emplacement to a syn- to post-D2 event and when this data is contextualized within the regional tectonics, we can constrain it to the late Svecokarelian orogeny which radiometrically has been constrained in Kiruna by syn-tectonic titanite to between ca. 1.81-1.79 Ga (Andersson et al. 2022).

Line 353: "~~west dipping~~": east-dipping, see figure 5

Figure 5 does not have any major west dipping structures. We would like to refer the reader to the listed references in this sentence for more details on the west-dipping structures outside of the Kiruna area.

Line 363: The authors should clearly demonstrate the occurrence of foliation in intrusive rocks and the relationships with cleavage in metamorphic rocks.
We have modified the figure showing foliation in intrusive rocks to improve the presentation of this result. Please see the response to the comment on Fig. 4H below.

Line 365: These statements are hardly to understand and seem speculative:

We have rephrased the text to improve clarity. While the interpretations are a suggestion for the discrepancy in the S1 development in the Kiruna mining district, we argue that they are not speculative when accounting for the regional deformation, magmatism, and alteration that is known in the area.

Line 399: This model is poorly based on analytical data described and illustrated in the previous text. It may be correct but the reader has no way to verify.
Based on the reviewer comments, we have rewritten our structural results section and added more detail so that this discussion figure can be verified with the presented data.

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Comments on Figures

Figure 3

there are 3 groups of poles. What is their meaning?

The groups of poles reflect specific mapping localities where there is a higher density of outcrops. The outcrop exposure in the area is ca. 5% and therefore, there is a moderate bias that occurs when several bedding measurements with relatively the same direction are taken from several outcrops in close vicinity to each other. We have added detail subfigures to Fig. 3 (now Fig. 4) to help illustrate this.

Figure 4

4D: low quality image, impossible to recognize asymmetrical shapes
Thank you for this comment. We have replaced the image with one with higher magnification to better show the porphyroclasts (now Fig. 5F).

4F: no evidence of mylonitic deformation. Porphyroclast are polycristalline aggregates
This sample is difficult to photograph because it is very fine grained, consisting of porphyroclastic and sedimentary material (fine-grained graphite). However, the whole sample shows dynamic recrystallization textures which is evidence of mylonitic deformation. The clast in this image has some fine-grained secondary (or metamorphic) mica, however it also occurs in the matrix as well. The clast itself and the wings show subgrain rotation (SGR) quartz recrystallization which is also a characteristic component of mylonitic textures. We have added additional annotations and images (now Fig. 5C, F) to provide evidence of mylonitic deformation.

4H: tectonic foliations are not recognizable in this image. Dark minerals (what are they?) do not have a preferred orientation
The S1 tectonic foliation in this image is best seen as pervasive cleavage planes. The foliated minerals include potassium feldspar, albite, and quartz. The S2 foliation also includes potassium feldspar, albite, and quartz, but in this image one can also see fine mafic minerals (biotite and amphibole). The dark patches that occur on the surface of the outcrop are lichen and weathering artifacts. We have added an additional annotation to help show the tectonic foliations but do not have a higher resolution photo (Fig. 5E, new manuscript).

4J: is this a shear band? I doubt. are tourmalines static?
We agree that the features and shear sense are not clear enough from this image and have removed it from the figure.

4K: the orientation of the S planes is wrong. The correct orientation is top to SE
We agree that the features and shear sense are not clear enough from this image and have removed it from the figure.

4L: not so evident!
We agree that the features are not clear enough in this photograph and unfortunately do not have one of better resolution. We have removed it from the figure.