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Dear editor Prof. Dr. Virginia Toy:

On behalf of my coauthors, I would like to thank you for the opportunity to revise and resubmit our manuscript no. egusphere-2022-1475 titled, "**Structural framework and timing of the Pahtohavare Cu ± Au deposits, Kiruna mining district, Sweden**." We found the reviewers' comments to be helpful in improving the organization, clarity, and scientific content of the manuscript and we have carefully considered and responded to each point and comment.

Both reviewers indicated a lack of clarity in the organization and language of the manuscript and additionally indicated that the research question was unclear and unmotivated. We have rewritten the introduction section in order to improve the structure, highlight the research question, and motivate the significance of the study. Additionally, according to the reviewers' input, we have restructured and rewritten the presentation of the structural results and have modified the discussion section to complement these changes and improve clarity.

Reviewer 1 indicated important information needed to be added including more structural measurements on the map in order to verify interpretations, supporting geophysical data, and deposit-scale maps of the epigenetic Pahtohavare localities. We have addressed this by adding more structural data as well as two new subfigures to the geological map so that our interpretations can be verified with the surface ground measurements (Fig. 4, 4A, 4B, new manuscript). Furthermore, we added an aeromagnetic anomaly map (now Fig. 3) and new deposit maps with structural data collected from co-author O. Martinsson during the 1990s (Fig. 6, new manuscript). We also added more referencing and annotations to our figures in order to improve coherency and compatibility of the figures throughout the manuscript.

Reviewer 2 indicated that tectonic structures and relationships were poorly described. To account for this, we have modified the text in the background, results, and discussion sections to improve upon this point and add clarity to the manuscript. We have added more annotations to figures to help with visualization for the readers.

We have included individual responses to each review report in which we address each comment the reviewers made. Our responses are always in red font following a peer review comment.

All authors have approved the manuscript and agree with its resubmission to *Solid Earth*. Please address all correspondence concerning this manuscript to me at leslie.logan@ltu.se. Thank you again for your consideration of this manuscript.

Sincerely,

Leslie Logan

Comment on egusphere-2022-1475, RC1

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 topic is interesting and relevant for understanding the relationships between different deposits types and their regional structural framework, which eventually, will aid in exploration of new deposits. The paper fits well the scope of the journal. There is new data, but it is unclear how representative it is (see P2 and comments to Fig. 3 below). The manuscript is written in a clear and understandable way.

However, the manuscript has several major shortcomings associated with i) defining the key questions, ii) presentation of the data and iii) subsequent structural interpretation (see points P1 to P5 below). As such, the new structural interpretations may not be verified from the presented evidence, and their correlation with regional geology, and further utilization in solving the relationships of the diverse mineralization of the study area are not justified. For the above reasons, the paper needs substantial improvement, and another round of review.

- **P1:** The study is not motivated as no specific research questions have been stated: The overall global IOA vs. IOCG problematics is described, but the manuscript does not state which are the key questions or hypotheses in applying or testing the concept to the area of the present study.

  Thank you for pointing this out and we agree that the key questions need to be clear to the reader. The main purpose of this study was to determine the relative timing of the formation of the Pahtohavare Cu ± Au deposits (which are currently unknown) by investigating the structural relationships of the ore and contextualizing them within the regional tectonic evolution. This is significant to the broader scientific community because there are currently no studies from the Kiruna mining district that assess the IOA and IOCG mineralization together from a mineral systems perspective and the respective tectonic settings. While the timing of the Kiirunavaara IOA deposit is well-constrained within the context of the Svecokarelian orogeny, the Pahtohavare deposits are not. The introduction section has been modified to clarify the purpose of the study.

- **P2:** The required geological background to justify the research questions (P1) is not provided.
  - In particular, the regional alteration-structure-mineralization features are mentioned (lines 22-23. 24-26, and later in Section 2.1), but their mutual relationships and role in formulating the research questions is not explained. Information such as that on lines 302-305 should be included in the introduction.

    Thank you for this comment. We have clarified the research question in the introduction which we believe provides better structure for the readers to understand the relationship between the alteration-structure-mineralization described in the introduction and background sections. Additional details have

been added both to the introduction and to the background sections to improve upon this point.

We have also moved lines 302-305 to the introduction.

- The structural description only characterizes bulk shortening directions of the main orogenic phases, but largely lacks information about the structural geometry and the character of the faults (trends, dips, kinematics, timing) and their relationship with alteration and stratigraphy. This information is required to justify the presented crustal evolution models (Fig. 6), as the model heavily leans on the presence of an extensional fault networks and reactivations along the included faults (which is justified as such!)

  Unfortunately, trends, dips, and kinematics of the extensional faults formed during the back-arc extension phase of the Svecokarelian (and possibly the early Paleoproterozoic rifting) have not been described in literature because of reactivation and overprinting of these structures from the later deformation events. However, we have added more information on the orientation of the early Paleoproterozoic rift structures, known kinematics of the shear zones for the different Svecokarelian deformation events, and added a new sub-section that describes local structures and the structural framework of Kiruna.

- **P3:** The introduction is missing the statement of the main outcome of the work (claim); presently the phrasing is (l. 56) "… investigation was conducted…", which leaves the work unmotivated. Please state clearly the main outcome of the work and its local and global significance, with respect to both the overall geological understanding and applicability in exploration (if any)

  Thank you for this comment. We have added a motivation and significance statement to the introduction which greatly improves the structure and clarity of the manuscript.

- **P4:** Presentation of input data: The presented structural interpretation (Figs. 3, 5) is not backed up by the description of the used data, as the spatial location and coverage of the outcrop observations and the drill-hole data is missing. No geophysics or other supporting information is provided either. There is a significant mismatch between that presented on maps and stereograms (see comments for Fig. 3 in particular). The location and largely also the orientation of the field and microscopic photos are missing. Introduction of structural data is not systematic (see e.g. comments regardings lines 156-167)

  Thank you for this point. The authors originally decided to present only the main structural results (i.e. reducing the number structural measurements reported on the map) because of the crowded result of reporting all the data on the map. However, we agree that this leads to nontransparent presentation of the data. We have adjusted the figure to include more surface mapping measurements, outcrop coverage, and locations of the microscopic images. We added the drill hole localities to the 3D model in Fig. 5 (now Fig. 7) as well as a full data map as a supplementary figure (S1). We also provided an aeromagnetic anomaly map (now Fig. 3) to support the interpretation. 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 was conducted from the 1990s but has not previously been published. It adds significantly to the manuscript and the new surface structural measurements from Southeastern open pit have been added to the stereoplots in Fig. 3

(now Fig. 4C-E). Furthermore, we have rewritten the structural results section to improve the presentation of the data according to your general and specific comments.

- **P5:** Structural interpretation: The lack of spatial data for the used input points (P4) makes it impossible to evaluate the validity of the structural interpretation. There are inconsistencies regarding the geometry of interpreted cross-sections, modelled anticline (antiform) and the orientation distribution of the bedding data. Reasoning behind the presented kinematic interpretations of the shear zones are not given in adequate detail (e.g. lines 191, 268)

  We have modified Fig. 3 (now Fig. 4) to be more transparent with the presentation of spatial data and have clarified the geometry of the fold and distribution of bedding data in the text. We have also rewritten and expanded our presentation of data from the shear zones to improve clarity and help with evaluation of our interpretations. The discussion section 5.1 has been rewritten to improve the connection between the presented data and the interpreted results.

Specific and technical comments:

Comments on Introduction

Line 21: Start the introduction with i) the global IOA-IOCG problematics, then proceed to ii) Kiruna deposits and geology, and based on these, develop research questions that can be a) used to improve the understanding about the IOA vs. IOCG in the Kiruna area (relevant questions are stated on lines 305-309, and should be included in the introduction; see P1), and b) solved with the available dataset and methods.

Thank you for this comment. We have rearranged the introduction section according to your points and have added more information about the purpose of the study.

Lines 34-37: These relate to the implementation >>> move to lines 55-59 (original line numbering)

We have rearranged this sentence to improve the structure of the introduction. Thanks.

Comments on Background

Line 112: change “direction” to “orientation”

This has been revised in text.

Line 113: Please indicate the trend of the conjugate faults.

We have added this to the text.

Line 115: A word appears to be missing in the title

We have revised the title for section 2.1.4.

Lines 116-117; 127-128: Please go directly to the point/subject in the first sentence of the section (applies to other sections as well). Now the first sentences are “empty”, which reduces the effectivity of the writing.

We have modified the text to improve the effectivity of the writing.

Line 118: “Rektor” is not shown on map. Please make sure all the locations cited in the text are visible on the figures.

Thank you for this comment. We have added an additional annotation for this location to the figure and cross checked that localities are properly cited in the figures or described in the manuscript to improve clarity.

Line 121: “formation” of what? Please explain!

We have reworded this sentence to improve clarity.

Line 133: unclear, please rephrase!

We have rephrased this sentence.

Line 142: Include “Kiirunavaara Group” in the legend of Fig. 3.

Thank you for this comment however we think that adding this subheading to the legend will be inconsistent with the current format which separates the rock sequences by relative age. Additionally, the Kiirunavaara Group is also too long to include after each of the names for Hopukka and Luossavaara formations. We prefer to keep the legend in its current format however have added the Hopukka or Luossavaara formations in parentheses when we refer to the Kiirunavaara group to help the reader refer to the geologic map.

Line 144,149, 252 + others): “Above the Luossavaara formation are a series….”. This is not good English, please rephrase to e.g. “ The Luossavaara Fm is overlain by ….”

We have done some revising, however, some text has been left with its current format to reduce unnecessary repetition of the same phrasing.

Line 146: Move the reference to the structural character of the unit in a new Section (2.2.2) explaining the local structure

We have moved this information to the new section (2.2.2.) to explain local structures.

Lines 156-167: Include this in a new section, which should include, in the following order: i) the relevant structural geometry of the area, with particular emphasis on the faults, ii) the known kinematics of the faults, iii) the known ages of the faults (and other deformation)

We have added a new section (2.2.2.) explaining the local structures and emphasized the previous knowledge on the faults in the district.

Line 163: “central Kiruna” >>> please be more specific and refer to a feature annotated on the map

We have added an annotation to the map and more description to the text.

Line 165: “… kinematics…” but along which structure, please explain!

We have added more information to the text.

Line 180: “… coeval with syn-volcanic faulting…” >>> Is this 1.90 or 1.89 Ga; please add an age.

We have added an age to the text.

Line 191: What is the dip and kinematics of this shear zone? (If known from earlier work)

The kinematics of the shear zone have not previously been reported with structural data and is presented in the results and discussion sections of this paper.

Line 194: Please explain in adequate detail which is the structural and lithological control. Later on (lines 198-200) there is some reference to hot lithology, but this is too far away from the statement on line 194 to be followed, and the type of structural control is not described. This is highly relevant for this investigation, as your work needs to either confirm or disprove the earlier interpretations, which can then be further used in confirming the working hypotheses (or questions) presented in the introduction.

We have rewritten the description of the deposits and included two new figures of the deposits (Fig. 6, new manuscript) to better present the structural context of the ore deposits.

Comments on Methods

Line 206: What are these localities? How are the input data distributed with respect to the mapped structure? This is a crucial issue to show as the reliability/uncertainty of the map is largely dependent on the input data; is the fold structure (hinge, both limbs) and all/some of the faults covered by field observations (or drill hole data (see line 218).

Thank you for this comment. Additional data has been added to Fig. 3 (now Fig. 4) to show where these mapping localities are and how they are distributed. Additionally, we have added a supplementary figure (S1) that shows the distribution of all of the measurement and observation points.

Line 211: What is the purpose of the sampling, how many samples were taken in total? Are (all) the samples oriented (many of the sections in Fig. 4 show no orientations)?

The purpose of the sampling was to study structural controls on mineralization, and this has been added to the text. Unfortunately, none of the drill cores from the Pahtohavare area are oriented, so oriented samples were only possible from field samples.

Line 218: From where are the drill holes? Show on a map/sections!

We have added the collar locations of the drill holes to the 3D model and have added a supplementary table with the drill hole names and locations (Table S1).

Comments on Results

Lines 232-233: Remove the first line; this is already told.

This has been edited in the manuscript.

Lines 237 + 238: See comments for Fig. 3 regarding the geometry of the antiform. Parasitic folding should follow the overall geometry of the fold, and as such does not explain the scatter in bedding

orientations. Please also be more specific in the description: e.g. Do not use “somewhat irregular” but instead describe the style of scatter or clustering on the stereograms, and link that specifically to the limbs and the hinge domain of the fold.

We agree that this phrasing was unclear. We have changed the phrasing as well as added a subfigure to Fig. 3 (now Fig. 4A) to clarify. We also 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 one parasitic fold measurement alone does not give the full picture, but unfortunately this 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.

Line 239 + 245: Location of the Pahtohavare open pit + Saarijärvi is not shown on the maps. Please add this information.

We have added the labels of the Pahtohavare deposits to the map and have added a better description of the Saarijärvi locality to the text. We also put a figure reference in Fig. 2.

Lines 255-259: These belong to the discussion (normally no references allowed in the results). What is non-coaxiality of strain based on? I can’t see the evidence.

The sentences with the reference have been removed from the results section. The non-coaxiality of strain is based on the shearing textures such as the S-C fabric and asymmetric porphyroclasts observed in thin section. The section has been rewritten to improve clarity.

Line 263: Where is this shear zone, please indivcate!

We have added a figure reference to (now) Fig. 4B to show the locality of the shear zone.

Line 264: “mineral lineation … shows a moderate oblique-reverse movement…” >>> not true as it only shows the relationship between the horizontal and vertical slip, NOT the shear sense, which needs to be derived from shear-sense criteria

The mineral lineation occurs on a near vertical foliation plane and can either be interpreted as oblique reverse or oblique-normal with a dominantly reverse/normal movement. We interpret oblique-reverse as the most probable geological explanation for forming the anticline bound by the NW-SE trending Pahtohavare shear zone.

Line 268: “sinistral oblique-reverse” >>> With respect to what deformation zone? What is the evidence? To me the NNW-SSE carbonate veins in Fig. 3D indicate vein-opening due to dextral slip along the bounding NW-SE fault/shear zone.

We have added that this movement is with respect to the NW-SE trending Pahtohavare shear zone. The data we have on shear sense indicators is unfortunately not conclusive enough (it could be that the shear zone has been reactivated as well) and we would like to highlight that the steep dip of the shear zone given by the local shear zone measurements (~80°) would indicate a dominantly reverse or normal movement compared to sinistral or dextral.

Line 271: Where are the tension gashes documented?

We have made the text more specific.

Lines 273-274: This is background information which needs to be moved to the Geological setting (see main comment P2b)

Thank you. This has been moved to the background section.

Lines 276-280…: This can't be linked to the figures nor evaluated as no spatial reference to the DHs is given in this manuscript (see P4).

The drill holes used for the 3D model have been added as collar locations to provide spatial reference.

Comments on Discussion

Lines 292- …: The discussion is quite unfocused and repetitive with earlier parts of the manuscript as the research questions are not adequately defined (P1)

We have rewritten large parts of the discussion section to provide a better focused discussion.

Lines 333-335: The relationship between the vein orientations and the derived kinematic interpretations or the kinematically linked faults/shear zones is either vague or not given at all (see also line 268).

Thank you for this comment. We have rewritten the discussion section and expanded on the vein orientations and derived kinematic interpretations in the text.

Line 341: What actually are the Pahtohavare deposits like? Now the geometric style of the deposits are just very roughly indicated in Fig. 7, whereas other figures only show their location.

We have included two new deposit maps based on your comments in this peer review (See response to Point 4). The deposits geometries are now described in more detail in the background, results, and discussion sections.

Lines 349-358: This information needs to be used in defining the research questions in the introduction, and the essential details needs to be included. For example, earlier considerations about the crustal level vs. the style of deformation need to be included as they are required in correlating the results of this investigation with the regional geology.

This information is not the motivation behind why the study was conducted but rather it is provided to give background for discussing a result from this study that conflicts with previous structural interpretations from the geology around Kiruna town. We have modified the opening sentence to better structure the discussion.

Line 384: Add the name of the SZ on the map.

We have added the Pahtohavare shear zone (PhSZ) onto the map (now Fig. 4) and Figs. 2, 6, and 7 (now Figs. 2, 8, 9).

Comments to figures (many of which are linked to general comments P1-P5)

Fig. 2:

- Please provide a cross-section to illustrate the relationship between the stratigraphy and the structure e.g. across the Luossavaara deposit. Annotate the Luossavaara deposit on this map (see Fig. 7)

  Thank you for this comment. However, the structural setting of the Luossavaara deposit is out of the scope of this study and is currently the subject of another ongoing research project at LTU. We have annotated the Luossavaara deposit onto the map.

- What is the character of the ENE-WSW trending fault which separates the Kiruna and Luossavaara deposits? Are the Kiruna and Luossavaara deposits initially part of the same lens/layer, and later split into pieces? Or is the fault syngenetic + later reactivated?

  This is a good question with important implications and is currently being studied by a colleague at LTU. We prefer to provide structural details on the main study area for this work which is outlined in Figure 3 (now Fig. 4).

- Legend: Loussavaara Fm >> Luossavaara Fm

  This has been edited.

Fig. 3:

- Is there some geophysics available to support the map, or is it solely based on mapping data?

  The current map is a modified version from Martinsson (1997), but in general the geology in the Kiruna area has utilized aeromagnetic anomaly maps to continue lithological contacts through unexposed areas and to highlight major structural lineaments (e.g. Offerberg, 1967, Geological Survey of Sweden). An aeromagnetic anomaly map has been added as a new figure (Fig. 3, new manuscript).

- What is the distribution of the structural data?
  - Please include the location of the input data points; both surface mapping and drill-hole (DH) data? This could also be presented as a separate "data map", but preferably included into the existing map; there should be space for it.

    Thank you for this comment. We have added detail-subfigures to Fig. 3 (now Fig. 4) to better show the distribution of surface mapping data. The drill hole collar locations used in the 3D model have been added both to Fig. 5 (now Fig. 7) and to supplementary figure S1.

  - What explains the presence of sub-vertcal NE-SW and ESE-WNW foliation planes? They are not compatible with the distribution of the bedding data (and hence indicative of the presence of bedding-parallel foliation); are they spatially associated with the faults?

    We first want to note that the foliation depicted in Fig. 3 (now Fig. 4) most likely consists of both S1 and S2 foliation directions and therefore, may contain foliation directions that are not compatible with the distribution of the bedding. Without clear overprinting field relationships, the authors chose to not separate these generations based on the stereonets alone.

For the NE-SW sub-vertical foliation: The localities that have steeply dipping NE-SW foliation planes on the stereonet are not associated with the faults. However, the character of the foliation measurements are of high strain. It is common in the Kiruna area that the foliation locally overturns in areas. If this is the case, then we would argue that the foliation is still compatible with the distribution of the bedding data and overall geometry of the fold.

For the ESE-WNW sub-vertical foliation: The orientation for these foliation planes may be related to the second deformation event and represent axial planar S2 fabric to the Pahtohavare F2 fold. However, as mentioned above, we chose not to separate the generations of fabric due to the lack of clear S1 and S2 cross cutting field relations. Of the data with this subvertical orientation, three localities can be suggested to represent a foliation direction compatible with the NW-SE trending Pahtohavare shear zone due either a) a close spatial proximity of the outcrop to the shear zone (foliation measurement 80/214, seen on Fig. 3 original manuscript near the NW-SE trending Pahtohavare shear zone), and b) being a measurement from a small-scale shear zone in Pahtohavare Southern open pit. These spatial mapping measurements can be seen in the new subfigure Fig. 4B in the new manuscript.

- Structural interpretation and correlation between the structural data shown on the map and the stereograms (plots hereafter):
    - Very few tectonic symbols (bedding, foliation) are shown on the map. Together with the missing information about the input data used in compiling the map (structural point data, geophysics, level maps from the mine etc…), it is impossible to judge the reliability of the structural interpretation.

      We thank you for this comment and have added more structural symbols to the map and included two new subfigures that summarize the structural data in more detail (Fig. 4A-B, new manuscript). We have also included an aeromagnetic anomaly map (Fig. 3, new manuscript) to illustrate the geometry of the fold and local structures. Additionally, co-author O. Martinsson has provided a level map from the Southern Pahtohavare deposit and a surface map showing the ore location and additional structural data at Southeastern Pahtohavare deposit from work done in the 1990s (Fig. 6, new manuscript). This work adds significantly to the manuscript and the additional surface structural measurements have been added to the stereoplots in Fig. 3 (now Fig. 4).

    - No sub-horizontal bedding data is shown on the map (min dip value on the map is 40), but the plot shows a cluster with ~9 reading with a mean 180-190/30 (dipdir/dip) orientation. These data should locate on the southern limb of the fault, but the bedding dips in Section A-A´ of Fig. 5 show that all the dips on the southern limb of the anticline are steep.

      We have added more spatial mapping data to Fig. 3 by adding subfigures (now Fig. 4A and 4B) for specific high density mapping areas to account for this comment. However, we would like to note that the outcrop exposure in Pahtohavare does not allow for a perfect transect across the limbs of the fold and reconstruction of the bedding directions. For our case, the stereonets are important in showing the overall geometry of the fold that can be seen in the aeromagnetic anomaly map, despite that the ground spatial mapping data is limited (due to the approximately 5% outcrop exposure). For example, the cluster of bedding points that show a mean 180-190/30 are associated to a series of outcrops on the northern limb where there are multiple bedding directions in a relatively small area (approximately 200m x

300 m, see Fig. 4A, new manuscript), and is interpreted to represent parasitic folding.

While the stereonet shows that the fold is slightly overturned, previous mapping results (Martinsson 1997) has shown the southern limb is only locally overturned. The data collected in this project from the Southern Pahtohavare open pit shows bedding locally has a dip direction steeply towards the SE. Therefore, we have chosen to depict the geometry of the fold with steeply dipping bedding in the southern limb with a subvertical to inclined axial plane.

- Should the sub-horizontal cluster of bedding data (see previous point) be including in defining the statistical fold axis (β)? This question relates to understanding the geometry of the anticline:

  Yes, we argue that it should be included in the statistical fold axis. The geometry of the fold is best visualized with the aeromagnetic anomaly map (Fig. 3, new manuscript) and though the shallow bedding is located on the northern limb of the fold, the stereonet visualization of the structural measurements agrees with the geometry of the fold from Fig. 3 and from previously published description of the fold (Martinsson 1997).

  - The southern limb of the anticline appears to be separated from the hinge and northern limb by a fault. Should the geometry of these domains be treated separately instead plotting a common β -axis for all the bedding data?

    The brittle fault separating the limbs of the fold seen on the map has only local offset of the stratigraphy in the field (Fig. 3, now Fig. 4), however, it does not propagate past the upper greenstone units. Therefore, we argue the two limbs can both be used for constructing the statistical fold axis.

  - What causes the) is “flat-topped” character of the anticline (Section A-A´ in Fig. 5)? Flattening of the fold hinge along Section A-A´from SE to NW is not justified as shown above.

    The flat-topped character of the anticline was drawn to represent the curvilinear nature of the fold axis. We know that the fold axis plunges to the SE (~35°, now ~50° with the 1990s data from Southeastern open pit) from the stereoplot data, but we also measured a fold from the Southern Pahtohavare open pit that shows the fold axis dips near horizontally (03/090). Furthermore, a new subfigure from the northern limb of the anticline (now Fig. 4A) shows the plunge in this area is ~20°. We have redrawn the cross section to better illustrate our interpretation of the geometry based on the stereoplot data.

- Is there sedimentary way-up data? Should the “anticline” be “antiform”?

  There has been sedimentary way-up data reported in Martinsson (1997) including graded bedding and pillow lava orientations. However, the main evidence making this structure an anticline is that the older stratigraphy is found in the core and the younger stratigraphy at the rims.

Fig. 4:

- Orientations and sampling sites are largely missing and should be included.

Thank you for this comment. We have added orientations and sampling sites to (now) Figures 2 and 4.

- The figures are jumping back and forth from topic to another; please restructure to explain the geometries of the structural elements and their (cross-cutting) relationships, then proceed to the evidence about localized deformation (shearing, faulting), including the shear sense criteria

  We have rewritten the results section to have better flow and continuity.

- The character of the highlighted clasts in Fig. d are not discernible from the figure

  We have replaced Fig. 4D with a higher magnification image to better highlight the porphyroclasts (now Fig. 5F). Furthermore, full thin section microphotographs of the sample has been added as supplementary figures (S2-S3) to the manuscript.

- Add reference to the orientation of the thin section, and the interpreted sense of shear for figs. e) + f). Moreover, show the spatial context of section by indicating their occurrence on a map / cross-section. Within these, the microphotographs are not useful.

  The thin section depicted in Figure 4E-F is not oriented. Unfortunately, it is a limitation of the field area that none of the drill cores are oriented and therefore this reference cannot be given. However, we have revised to show the interpreted sense of shear and added the drill hole locality to the Fig. 3 (now Fig. 4).

Fig. 5:

- This is a nice 3D-illustration

  Thank you for this comment.

- The moderately SE-dipping fault in Section A-A´ doesn't intersect the section in the 3D-model. Please revise /extend.

  The moderately SE dipping fault is currently shown in the 3D model in the upper part of the greenstones (where it cross cuts the present day topography, and not the extrapolated topography). However, we have slightly modified the 3D model to improve clarity.

- What is the character of the discordant bottom contact of the pillow basalt; tectonic or depositional unconformity? Please explain and annotate in the figure accordingly.

  The character of the bottom contact of the pillow basalt is depositional and was accidentally drawn discordantly. We have updated the cross section according to the comments from this peer review to improve the figure.

Fig. 6:

- This tectonic sketch should cover the same area as Fig. 7 as the latter encloses also the major IOA deposits, which are not presented here. For this reason, this figure is not motivated in providing improved understanding about the relationship between the different deposits

types (Pahtohavare & IOAs), which in the beginning of the abstract is stated to be one of the major unknowns of the area, and as such, main aims of the study.

Thank you for this comment. We would first like to note that this sketch is not drawn to be a 1:1 depiction of the Kiruna mining district and is meant to be purely a conceptional hypothesis of how structural features could have developed in the area. However, we have added a label to depict the approximate location of the Kiirunavaara deposit.

The same scale problem applies to correlation with Fig. 1: Which of the WNW-ESE faults in Fig. 1 corresponds to the northern WNE-ESE fault in Fig. 7?

We have added labels to the figures 2, 3, 4, 8 and 9 (new manuscript) for the Pahtohavare shear zone (PhSZ), Kiruna-Naimakka deformation zone (KNDZ), and Svappavaara deformation zone (SDZ) to improve correlation between the figures. We would like to note that WNW-ESE SDZ in Fig 2 is cut off in Fig 7 (now Fig. 9).

>>> This is in fact a critical point for understanding the primary (syn-depositional) fault network and their potential control over the deposition of the supracrustal rocks:

1. The northern WNW-ESE fault constrains the lateral extent of the Hauki, Matojärvi and Luossavaara FMs so that they occur only to the north of the fault

   Since this figure is of conceptual nature, not all the possible basins have been drawn, so these units are not necessarily controlled by the single basin depicted in the concept.

2. By contrast, the depositional basin defined by the two opposingly dipping, WNW-ESE trending normal faults in Fig. 6a would suggest that the above FMs should have been deposited to the south of the northern WNW-ESE fault in Fig. 6. Northerly dip for both WNW-ESES trending normal faults in Fig. 6a could be more compatible with respect to the spatial distribution and thickness of the presented stratigraphic units.

   We agree that having a northerly dip for both normal faults could occur, but we would like to illustrate a simplified basin model with this concept. We also agree that the normal faults in Fig. 6a would suggest the formations should have been deposited to the south of the northern WNW-ESE fault, but the figure is meant to emphasize how the structures could have developed. The basin itself is much bigger and probably composed of several sub-basins.

   - a): The age should be max. 1.89 Ga = age of the oldest supracrustals

   The age has been modified in the figure.

   - Please clarify the timing relationship between the 1.87 Ga deformation event (Gig. 6b) and the deposition of the 1.89-1.85 Ga rocks; is there ongoing deposition at the time of this deformation event? In particular one would expect deposition of syn-faulting (1.87Ga) strata into the releasing bend of the N-S strike-slip fault (presently just teh Rakkurijärvi deposit is localized into this site).

   The deposition of the mid-Orosirian rocks is interpreted to have occurred during basin development (Andersson et al., 2021) between ca. 1.89 Ga and 1.87 Ga before the onset of crustal shortening phase depicted in Fig. 6B (now Fig. 8B). The exact depositional ages are difficult to know, however the Rektorn ore body yielded a zircon U-Pb age of 1.874 Ga (Westhues et al., 2016), which constrains a minimum age of the hosting Luossavaara formation. The timing of the deformation event is constrained approximately by pre- to syn- orogenic intrusions which suggest it took place between ca. 1.90-1.87 Ga (e.g. Cliff et al., 1990, Romer et al., 1994, Westhues et al., 2016, Andersson et al., 2021, Logan et al., 2022).

The releasing bend drawn near the Rakkurijärvi deposit is purely conceptual and drawn to loosely correlate with the geologic map. The deposit has been described to be hosted both in the Kurravaara conglomerate and the Kiirunavaara group volcanics. Further investigation of overlying rocks in the Rakkurijärvi area has not been conducted and is beyond the scope of this study.

Please replace symbols for the deposits so that the symbol better illustrates the location, shape and orientation of each deposit, as far as possible, in the given scale. This needs to be in line with the information presented in Fig. 7.

Thank you for your comment. The conceptual nature of Fig. 6 (now Fig. 8) is meant to show the general areas where the Pahtohavare and Rakkurijärvi ore deposits occur. Adding detail for the individual sub-deposits (total = 8 between Pahtohavare and Rakkurijärvi) that would match the respective shape and orientation is not possible within the space available. For example, Eastern Pahtohavare occurs as a horizon that would be difficult to draw as a plane (pre-tilting) in Fig. 6a-b. The Rakkurijärvi deposit geometry is known to a lesser extent, and is also beyond the scope of this study. However, we have modified the symbols to add Pahtohavare Early (Pah-$_E$) and Pahtohavare late (Pah-$_L$) to improve clarity for the figure.

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.

****

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.