List of changes se-2019-150

Dear topical editor,

In this document we list the changes made to the manuscript “se-2019-150” in accordance with the referee comments made by Dr. Qui (RC1) and Dr. Kolb (RC2).

The changes listed below can also be found as additional comments to each referee comment in the author’s response to each reviewer (attached). The numbered changes below correlates to the numbered referee comments in the authors response. For several changes, further explanation/motivation can be found in the additional comments to the referee comments in the authors response documents.

Some repetition do occur in the listed changes below but this is done in order show that we have considered each of the concerns of the reviewers.

Three new figures have been produced in order to clarify questions raised by the reviewers. Figure 4, Figure 16, and Figure 18 are new figures. Figure 4 is a summary of geological background information that we hope will help international readers. Figure 16 shows a metamorphic mineral association and its relation to deformation that was produced in order make the distinction between metamorphic and hydrothermal mineral associations clearer. Figure 18 is a summary map of hydrothermal alteration. One additional image was included in Figure 17. This image was down prioritized during the production of the first submitted manuscript, but since we could free space in Figure 17 by including Figure 16 this new image showing K-feldspar + epidote alteration could be included. We hope that this is ok since we think that the image adds information on how the potassic-ferroan alteration styles developed during D2 may appear in field.

Yours Sincerely,

Joel Andersson,
Lead and corresponding author
PhD candidate in ore geology
Luleå University of Technology
Department of Civil, Environmental and Natural Resources Engineering
Division of Geosciences and Environmental Engineering
SE-971 87 Luleå
Sweden
Phone: +46-920493549
Mobile: +46-730821280
e-mail: joel.bh.andersson@ltu.se

Review 1 Dr. Qui:

Changes in accordance with major comments

1. We have added a time-scale in Fig. 16 (Fig. 19 in the resubmitted manuscript) and included supracrustal rocks, intrusive rocks, and mineralization to clarify how these relate temporally to the deformation and hydrothermal mineral associations in the study area. In the summary of hydrothermal alterations, the bullet points now includes the parameters added to Fig. 19.

Changes in accordance with general comments

3. Labels have been unified. Abbreviations in figures have been explained in the captions.
4. Figure 7 (Figure 6 in previous version). We have added space between the images in accordance with the other figures in the manuscript.
5. We have removed the extra box in Fig. 8d (note that this is now Fig. 9d in the resubmitted manuscript).
6. We have added the area for each image in the caption of Fig. 15. (note that this is now Fig. 17).
7. We have changed the figure reference from Fig.15e to Fig.15g in section 6.4. (Fig. 15g is now Fig. 16a in the resubmitted manuscript).

Review 2 Dr. Kolb

We have changed the manuscript in accordance with the supplementary material (annotated PDF) provided by Dr. Kolb. The majority of the suggested changes were accepted. Where we have chosen not to change, this is motivated as a supplementary comment in the annotated PDF as well as motivated in the authors response.

Changes in accordance with the main concerns

1. Beyond the comments in the supplementary material attached by Dr. Kolb, we have reviewed the full manuscript, deleted parts of it and rewritten other parts, and reworded a number of passages where needed. Furthermore, terms are now used consistently, except the terms "phase" and "event" that are used interchangeable in the revised manuscript.
2. We have reworded passages that could be clarified by rewording throughout the entire manuscript. The text is restructured following the structure old-young except one paragraph in the Discussion on page 16 that is structured young-old. Motivation to the young-old structure of the paragraph can be found as a supplementary comment in the attached author response to RC2.
3. We have reformulated much of the text focusing on hydrothermal and metamorphic mineral associations. We have separated hydrothermal and metamorphic mineral associations into different figures (Fig. 16 and Fig. 17) and discuss these separately in the text. We now state already in the abstract that the hydrothermal mineral alterations linked to D1 may form part of one single hydrothermal system but that they are separated in this study on the basis of crosscutting relationships. This is also stated in the chapters of the paper. In the case of calcite alteration, we have clarified that it is restricted to mafic rocks and the role of carbonate alteration is discussed in the chapter Discussion. We have also produced an alteration map combining structures, aeromagnetics and alteration (Fig. 18).

Changes in accordance with detailed comments

1. We have changed "Palaeoproterozoic" to "Paleoproterozoic". 11 changes.
2. We have changed "sulphide" to "sulfide". 7 changes.

3. We have abandoned the prefix "meta" throughout the manuscript. Motivation to this decision is given as a last paragraph in the section 1. Introduction.
4. Where we suspect that mineralization can be read as a thing, we have changed the word "mineralization" to "ore" or "deposit" depending on context.

   Introduction. We have clarified the importance of the study and the introduction of the research gap as well as the scientific contribution.
   We have avoided repetition by deleting the second paragraph that includes a very general geological background and was originally written to "set the scene". Furthermore, background of how the study area relates to similar terrains worldwide has been added in accordance with the referee comment.

5. Regional geology: Stratigraphy together with a schematic overview of the timing of supracrustal/intrusive rocks, metamorphism, deformation, and mineralization is now included as Figure 4 and the text explains the figure.
6. Method: We have deleted the text mentioning Leapfrog in section “Methods”.
7. Results: We have worked further on the text to clarify the text and made sure that the text is organized from old-young and do not mix scales.

   Regarding consistent use of time scales throughout the manuscript, Ma is now used when geochronological data is presented (e. g. U-Pb zircon age at 1902 ± 4 Ma) and Ga is used when general geological times are expressed (e.g. The Svecokarelian orogeny 1.9-1.8 Ga).

8. Chapter 6.4.1 is now extended and moved to the end of the result chapter. In the summary, the information is repeated but set into context with supracrustal/intrusive rocks and mineralization in Norrbotten. This was done in accordance with comments from Reviewer 1 Dr. Qui.
9. All legends are changed in accordance with the referee comment and the comments made on the maps in the figure captions (in the annotated PDF supplied by Dr. Kolb). We have also included a figure reference to the new alteration map (Fig. 18) in Figure 2 and 3.
10. We have added information on statistics for density plots in Figure 6 (Figure 5 in previous version).
11. Page 1, line 16ff: We have clarified that the mineral alteration associations linked to D1 may form part of one single hydrothermal system but are treated as separate in this study because they show overprinting relations. The role of calcite is clarified in the discussion where late stage carbonate deposition in IOCG-systems is discussed as well as the possibility of down-welling of meteoric fluids in the case where calcite overprints the shear zone fabric.
12. Page 1, line 20: We have changed "brittle-ductile" to "brittle-plastic" throughout the manuscript. Where the text describes that a condition is brittle-ductile, this has been changed to describe the resulting structure as brittle-plastic. In some cases where a regional feature is described, "brittle-ductile deformation zone" has been changed to "crustal-scale deformation zone".

13. Page 2, line 1: The sentence on Page 2 line 1 was deleted. The sentence before was reworded in order to keep context.
14. Page 2, line 3ff: Could not find the repetition pointed out on page 2 line 3ff.
15. Page 2, line 12: We have changed all passages where rocks are described as Svecokarelian-related. The new term is Svecofennian. The term Svecokarelian is now restricted to the orogeny.
16. Page 4, line 25ff: The role of granulite facies metamorphism has been clarified in the sentence on page 4 line 25 ff. Also, "limited PT-modelling" was changed to "microprobe data".
17. Page 4, line 30ff: The text on Page 4 line 30 ff. has been clarified for the number of deformation events in northern Norrbotten.
18. Page 10, line 6: "Reverse" is now always before "dip-slip" in the manuscript.
19. Page 10, line 10ff: The paragraph including page 10 line 10ff was reorganized into two paragraphs. The information obtained from quartz fabrics and feldspar fabrics (as well as the metamorphic textures) have been clarified with support from literature.
20. Page 12, line 15ff: The paragraph on page 12 including line 15 has been reorganized. The paragraph is now 2 paragraphs, one focusing on scapolite-albite and one paragraph focusing on magnetite-amphibole. We have clarified the interpreted timing of scapolite veining.
21. Page 14, line 20ff: In order to clarify the text and figures, we have separated hydrothermal alteration and metamorphic mineral associations to different figures (Fig. 16, Fig. 17). The figure with metamorphic minerals is now Fig. 16 and includes 2 additional micrographs showing the timing of metamorphism in relation to D1 deformation (syn-tectonic growth of hornblende). Hydrothermal mineral associations are found in Fig. 17 and includes 1 additional image Fig. 17G. We have rewritten parts of and reorganized the full section 5.6. The text now clearly separates metamorphic and hydrothermal mineral associations. It describes the alteration styles from old to young and do not concentrate on a particular mineral, but rather on the mineral associations.
22. Page 14, Line 20 ff.: The paragraph including page 14 line 20 is rewritten. We link the metamorphic mineral association to dynamic quartz recrystallization textures and discuss a possibility to why lower temperatures (400 C°) are indicated by the quartz textures in the D1 shear zones in respect to the temperatures indicated by the metamorphic texture (>450 C°). We also discuss what temperatures (400 C°) that is indicated by the quartz textures in the D2 shear zones. Also, the paragraph is restructured to describe old-young according to earlier referee comments.
23. Page 15, Line 5: We have deleted the sentence in page 15, line 5.
24. Page 15, Line 6 ff: The text on page 15 line 6ff has been clarified by stating more clear where the areas are located in Fig. 1. The importance of the comparison is motivated in the text. Based on the findings in adjacent areas together with our results from the WSB, we have clarified that a pronounced deformation during D1 followed by weaker deformation during D2 forms the deformation systematics in this part of Norrbotten.
25. Page 15, Line 13 ff.: We have reorganized the paragraph on Page 15 line 13 ff. We describe the lineation from young to old in this paragraph. The reason for this is that the L2 is rather

straight forward whereas the classification of L1 requires some degree of speculation. By describing young to old, we spare the somewhat speculative part to the end of the paragraph.

26. Page 16, Line 20 ff.: We have deleted the sentence "These fold structures could have formed in a fold-and-thrust belt (Wright, 1988; Talbot and Koyi, 1995; Angvik, 2014) or, alternatively, during basin inversion (Andersson et al. 2017)”.

    We have inserted a new chapter before this chapter named "6.2.1 Pre-D1-event" where we explain why our structural model takes into account that the geological setting were extensional during the deposition of the supracrustal rocks of WSB. Text is moved from the paragraph including page 16, line 20 to this new chapter.
27. Page 16, Line 26 ff. We have clarified the sentence.
28. Page 17, Line 2 ff. We have clarified the timing of the metamorphic texture by adding two new micrographs showing syntectonic growth of hornblende.
29. Page 19, Line 4: We have added a discussion on the timing of scapolitization in Norrbotten referring to earlier geochronological studies with reported precisions.
30. Page 19, Line 10 ff.: We have deleted the text discussing the Cl/Br geochemistry and fluid sources. We have reorganized the paragraph.
31. Page 19, Line 17 ff: Text rearranged old-young throughout the manuscript except for one paragraph on page 16, which is structures young-old.

The timing of metamorphism have been clarified by adding two micrographs of syntectonic growth of hornblende in the metamorphic mineral association. Also, observations of metamorphic mineral associations have been separated from observations of hydrothermal mineral associations into two separate figures (Fig. 16 and 17).

We put the PT-information obtained by the metamorphic mineral association in relation to the dynamic recrystallization quartz textures in order to obtain more PT-information out from our observations.

We have compiled a map showing hydrothermal alterations and their relation to dominant structures and magnetics, Figure 18.

Final author response to referee RC1 Dr. Kunfeng Qiu on “Evolution of structures and hydrothermal alteration in a Palaeoproterozoic metasupracrustal belt: Constraining paired deformation-fluid flow events in a Fe and Cu-Au prospective terrain in northern Sweden” by Joel B. H. Andersson et al.

Dear Dr. Qui,

We were happy to receive your review of our manuscript submitted to Solid Earth (reference no. SE-2019-150) and thank you for taking the time to read the paper and critically appraise its content. We hope that the answers provided below will satisfactorily address your comments and lead to an improved, higher quality manuscript for publication in Solid Earth.

Joel Andersson,
Lead and corresponding author
PhD candidate in ore geology
Luleå University of Technology
Department of Civil, Environmental and Natural Resources Engineering
Division of Geosciences and Environmental Engineering
SE-971 87 Luleå
Sweden
Phone: +46-920493549
Mobile: +46-730821280
e-mail: joel.bh.andersson@ltu.se

Answers to major comments:

1. **Comment from referee:**

   The authors have constrained the timing of deformation by previous geochronological data. In my opinion, the paper will be more attractive if the authors could add some basic geologic characteristics, geochronology, and time scale of mineralization in the figure 16 and section 6.4.1

   Authors response:

   We agree that adding the suggested types of information to Figure 16 and Section 6.4.1 would be useful ideal and we consider such a holistic understanding of the regional geology as the ultimate aim. However, in order to do that in a concluding figure and text we would prefer more evidence and better regional control. At this stage of geological research in the Western Supracrustal Belt (WSB) area, we can discuss absolute time constraints and we can construct hypotheses based on our new geological data and geochronological works presented by other scholars in adjacent areas.

   In order to meet this referee comment, we will need to merge our own data with results from litterature.

   Author's changes in manuscript:

   We will clarify Fig. 16 and section 6.4.1 by adding geochronological constraints on lithologies, mineralization and deformation based on available data in the literature.

Answers to general comments:

1. **Comment from referee:**

Please unify the labels of the figures (uppercase or lowercase) in text and figure and explain the abbreviations.

Authors response:

We will go through the manuscript and adjust accordingly.

Author's changes in manuscript:

Changes will be made according to the referee comment.

2. **Comment from referee:**

Figure 6: Add some spaces between the images

Authors response:

We agree.

Author's changes in manuscript:

Spaces will be added between images in Figure 6 in accordance to the other figures in the manuscript.

3. **Comment from referee:**

Figure 8d: Delete the extra box.

Authors response:

Definitely, thank you for pointing this out.

Author's changes in manuscript:

The extra box in Figure 8d will be deleted

4. **Comment from referee:**

I suggest the authors add the location (area) in the captain of figure 15. It is difficult to link the coordinates to the different key areas.

Authors response:

We agree that adding the areas in the captain of figure 15 will clarify figure 15.

Author's changes in manuscript:

In figure 15, each image will be linked to the area in which is the observation is made.

5. **Comment from referee:**

In section 6.4, the author mentioned hornblende + epidote + plagioclase assemblage in figure 15e. But there is no corresponding information in the figure.

Authors response:

The correct figure reference should be 15G and not 15E. We apologize for this typing error.

Author's changes in manuscript:

The typing error in section 6.4 will be corrected in the resubmitted manuscript.

Final author response to referee RC2 Dr. Jochen Kolb on "Evolution of structures and hydrothermal alteration in a Palaeoproterozoic metasupracrustal belt: Constraining paired deformation-fluid flow events in a Fe and Cu-Au prospective terrain in northern Sweden" by Joel B. H. Andersson et al.

Dear Dr. Kolb (JK),

We are happy to receive your detailed and thorough review on our manuscript submitted to Solid Earth (reference no. SE-2019-150). The review is detailed as well as targets questions that have implications on the overall interpretation made in this study and has the potential to significantly improve the manuscript.

We are currently reworking the manuscript. Attached is the annotated PDF-file "se-2019-150-RC2-supplement" with comments on each suggestion. Where we have preferred not to change or to change in another way than suggested, we try to motivate this in the answer to the comment in the annotated PDF. Very important to note is that this document only shows the initial reworking of the manuscript and addresses only the direct suggestions made in the PDF-file "se-2019-150-RC2-supplement". We will continue to rewrite the manuscript in accordance with the referee comments as described in the answers to the comments below.

Joel Andersson,
Lead and corresponding author
PhD candidate in ore geology
Luleå University of Technology
Department of Civil, Environmental and Natural Resources Engineering
Division of Geosciences and Environmental Engineering
SE-971 87 Luleå
Sweden
Phone: +46-920493549
Mobile: +46-730821280
e-mail: joel.bh.andersson@ltu.se

Response to the main concerns:

1. **Comment from referee:**

   The wording of the manuscript is poor. The authors are imprecise and don't use the language of our science strictly. They mix up terms and use language that makes understanding of their descriptions difficult or impossible. The entire manuscript needs careful rewording and possibly the care of a native speaker."

   Authors response:

   The linguistic and terminology suggestions made by JK in the attached document "se-2019-150-RC2-supplement" significantly improved the manuscript and we will continue to work on the language as suggested in the detailed comments below. Changes already made to the manuscript are found as answer to comments in the attached document "se-2019-150-RC2-supplement". Co-author Edward Lynch (EL) is a native English speaker and he has been involved in the full writing process. EL will carefully assess the manuscript again from an English language and wording perspective before resubmission.

   We are also continuing to work on the manuscript to make sure that geological terms are used correctly and consistently in accordance with the detailed comments below. However, already at this early stage of reworking the manuscript, we note that some of the terms criticized by JK are indeed used correctly (see below).

Author's changes in manuscript

The majority of the suggested changes in the supplementary material “se-2019-150-RC2-supplement” attached by JK have been accepted and corrected in the manuscript. Regarding the usage of some terminology we disagree with the review. As pointed out by JK in the detailed comments, the manuscript does contains inconsistent use of some terms, and this will be corrected in the resubmitted manuscript. However, we regard that some terms criticized in the supplementary material (se-2019-150-RC2-supplement) but not discussed further in the detailed comments should not be changed. These suggested changes of terminology include:

“Deformation phase” suggested to be changed to “deformation stage”. The argument by JK is that the word or term ***phase*** *“is a term that in our science general means mineral or molecule.”*

Motivation: The term “deformation phase” is commonly used in structural geological literature. In the manuscript, we use the term “deformation phase” according to the definition by Fossen (2010): "A deformation phase is a time period during which structures formed continuously within a region, with a common expression that can be linked to a particular stress or strain field or kinematic pattern".

“Deformation event” suggested to be changed to “deformation stage”. The argument by JK is that an “event” is very short lived, e.g. an earthquake.

Motivation: This is a good point and we agree that the term “event” intuitively gives the impression of a geologically instant happening. However, neither “phase” or “event” implies a length of duration of a particular geological process. The term “deformation event” as well as “metamorphic event” is used frequently in our science and are used in scientific journal papers as well as books. See for example the paper by Kärki & Laajoki (1995) in the Journal of Structural Geology where both the term “deformation event” as well as “deformation phase” are used interchangeably. Vernon & Clarke (2008) also use the usage of “metamorphic event” to generally describe the occurrence of a stage of metamorphic process or change in space and time, but without any specific absolute constraints on its duration.

“Mineral association” suggested to be changed to “mineral assemblage”.

Comment: We apologize for the inconsistent use of the terms “mineral association” and “mineral assemblage”. Both terms are used in the revised manuscript. However, in the resubmitted manuscript, the term “mineral association” is the preferred term we wish to use throughout the paper.

Motivation: We have chosen to use the term “mineral association” instead of “mineral assemblage” in this manuscript because the term “mineral assemblage” implies equilibrium between the minerals assigned to a given assemblage. Many of the mineral associations described in this manuscript may be true mineral assemblages, but confirmation of this would require further studies beyond the scope of our mapping study (e.g. microprobe analysis and PTX modelling). We consider such a study an important “next step” in the geological research of the Western Supracrustal Belt (WSB) and such a study would justify a journal publication on its own.

We consider the definition by Pirajno (2009) as suitable in this context and he makes the following distinction between “mineral assemblage” and “mineral association”: “A mineral assemblage refers to a group of minerals that formed more or less at the same time and are stable together. A mineral assemblage essentially defines the physico-chemical conditions of the system. A mineral association, on the other hand, is a group of minerals that occurs together, but are not necessarily in equilibrium and did not form at the same time. “

Change “movement” to “deformation”.

Motivation: We prefer to keep the use of “movement” in all cases where the kinematics of a structure is in focus. Our argument is that “deformation” by its nature can be “brittle” or “ductile” or a combination of both, but cannot be assigned the adjectives “sinistral”, “dextral” or “reverse”, which describes the relative movement of e. g. a hanging wall block of a normal fault with respect to the footwall block.

2. **Comment from referee:**

The authors need to reword the entire manuscript and need to follow the two principles of writing a geology manuscript: (1) old structures or rocks need to be described before their younger counterparts; and (2) data needs to be presented and described first, interpretation follows.

Authors response:

Already after working through the document according to the supplementary material “se-2019-150-RC2-supplement”, the manuscript has improved in line with this comment. We expect further improvements on this point in the resubmitted manuscript when the detailed comments below have been taken into account.

Author's changes in manuscript:

We will change in accordance with the referee comment.

3. **Comment from referee:**

The metamorphic and hydrothermal assemblages need to be described in much more detail. What is their relationship to foliations and lineations? The mineralogy of hydrothermal alteration zones depends on P, T, X and physicochemical parameter. This results in the situation that hydrothermal mineral assemblages may not only vary on relative timing in the geological evolution and along a PT path. They also vary with host rock composition, fluid composition, distance from the main fluid conduit etc. This causes in many situations complex hydrothermal alteration patterns and zoning in hydrothermal ore deposits. This is well-described in many similar systems elsewhere in the world. The authors need to be more careful with their petrological data and must observe and interpret with much more detail. It would help the reader, if the authors could add hydrothermal alteration zones to their lithological and structural maps.

Authors response:

With this comment, JK makes precise and valid points highlighting the complexity of studying hydrothermal alteration systems. One of our aims in the paper was to keep a descriptive or qualitative tone and try not to over interpret our field observations, particularly regarding the type, style and distribution of hydrothermal alteration.

We have discussed several times whether we should try to produce alteration maps for the study area. During our work we realized that such maps would fit into the overall aim of our study but that spatial distribution uncertainties would be extremely high since the amount of outcrop in the WSB is approximately 1% of the surface area (typical for Norrbotten). Nevertheless, after receiving this comment on including alteration on maps we agree with JK and will go forward with a regional-level alteration map for the study area.

Author's changes in manuscript:

We will include a figure showing a belt-scale alteration map. It will be based on mapping observations from the Geological Survey of Sweden (of which the 3rd author has directly contributed), combined with our own field observations from this work. The map will contain high uncertainties and we will try to communicate these uncertainties using appropriate symbols and colours, and a qualitative/descriptive approach in order to be as clear as possible.

Response to the detailed comments:

1. **Comment from referee:**

Palaeoproterozoic: The stratigraphic commission has changed the general way of spelling this into Paleoproterozoic (also Archean, etc.)

Authors response:

Thank you for pointing this out.

Author's changes in manuscript:

It will be changed throughout the manuscript.

2. **Comment from referee:**

Sulphide: The now generally accepted spelling of this word in economic geology papers is “sulfide”.

Authors response:

In the manuscript we have kept the language to British English.

Author's changes in manuscript:

“Sulphide” will be changed to “sulfide” in the resubmitted manuscript.

3. **Comment from referee:**

Title: Delete “meta” and use supracrustal belt. I personally prefer “greenstonebelt”, because often not all of the rocks contained in such a belt are strictly supracrustal (you also describe dykes for example).

Authors response:

We agree on that the prefix "meta" is not needed in the title. We also consider it as not needed throughout the manuscript since all rocks in this study are metamorphosed to some degree.

The composition of the volcanic rocks in northern Norrbotten do bear some similarities to greenstone belts elsewhere and based on chemical composition alone, it is hard to resolve the tectonic setting (e. g. read back-arc vs. mantle plume). However, the volume of basalts are subordinate in comparison to andesite and felsic compositions, which makes an important difference to the Rhyacian "true" greenstone belts that are found at stratigraphically lower positions in Norrbotten (see Bergman et al. 2001, Bergman 2018). Our main objection towards the use of "greenstone belt" for the Orosirian (c. 1.9 Ga) supracrustal belts is that it would introduce confusion into the Norrbotten geological literature. The term "greenstone belt"or "greenstones" in a Norrbotten/north Fennoscandia context has never been used to describe Orosirian rocks despite over 100 years of geological research in the area. Instead, this term is restricted to Rhyacian (c. 2.1 Ga) rift-related mafic rocks that forms part of a large igneous province stretching from northern Norway to Russia. However, we would encourage a discussion of the use of the term "greenstone belt" in Norrbotten but since we are not convinced that that "greenstone belt" is the best term we don't want to initiate the terminology in this study.

A minor but important objection towards the use of "greenstone belt" in this context is that the term "greenstone belt" is a rather loosely defined term and would require a detailed definition if used in this study. See Lynch et al. (2018) for a short summary regarding use of names and terms for greenstone-type rocks in northern Norrbotten.

Author's changes in manuscript:

We will exclude the prefix "meta" throughout the manuscript and motivate this early in the text.

We prefer to keep the term "supracrustal" throughout the manuscript.

4. **Comment from referee:**

Mineralization: "Mineralization" is a process not a thing. Check your wording accordingly.

Authors response:

We agree on that mineralization is not a thing.

Author's changes in manuscript:

We will reword all passages in the manuscript where the term "mineralization" is described as a thing.

Comment from referee:

Introduction: There is a lot, which is repeated and detailed in later chapters. The introduction should introduce the problem and specify the research questions and the approach. This is only partly true here. Why is the study important? What will the addition to science be? Why is relating hydrothermal alteration to structures important? How is the situation elsewhere in similar terranes with IOCG deposits, Canada, Brazil, Australia (e.g. Tennant Creek, Mount Isa), Mauritania. . .. . ..?

Authors response:

We have reviewed the introduction and we do not find the chapter too bad. However, the points highlighted by JK in the referee comment is very important and we think that the manuscript will improve by address these question in a clearer and more concise way.

Author's changes in manuscript:

We have changed the chapter in accordance with the supplementary material “se-2019-150-RC2-supplement”. We are currently working on improving the introduction further by addressing the questions raised in this referee comment.

5. **Comment from referee:**

Regional Geology: This chapter is poorly worded and poorly structured. The data and observation must be presented before interpretation. A clear stratigraphy is necessary. I suggest preparing a table or a sketch to help the reader. In the text, the nomenclature has to be used strictly and consistently.

Authors response:

We agree that a figure is needed showing the stratigraphy of northern Norrbotten.

Author's changes in manuscript:

We will reword and try to restructure the chapter as well as make sure that nomenclature is used consistently. A figure will be produced explaining the stratigraphy of northern Norrbotten.

6. **Comment from referee:**

Methods: No Leapfrog model is shown in this paper – adjust this chapter to the methods used for generation of the data presented in this manuscript.

Authors response:

We apologize for this. Leapfrog was used initially in order to group and plot data as well as to produce initial stereographic analyses. However, this work is not presented in the manuscript and we agree that it should be deleted.

Author's changes in manuscript:

We will delete the text mentioning Leapfrog.

7. **Comment from referee:**

Results: Describe your data from old to young. This is a geology paradigm that makes sense, because old structures are always overprinted by young structures. Don’t shift between scales. Make a description at regional, district, local, outcrop, sample, thin section scale and organize accordingly.

Authors response:

We agree that some passages in the text require restructuring (old-young) and that scales, especially time scales (e. g. Ma and Ga) are mixed in the text. Many such passages have been pointed out in the supplementary material “se-2019-150-RC2-supplement”.

Author's changes in manuscript:

We have made the changes suggested in the supplementary material “se-2019-150-RC2-supplement” on this comment.

8. **Comment from referee:**

   Chapter 6.4.1 is needed much earlier in the manuscript.

   Authors response:

   Chapter 6.4.1 is a summary section, which is usually given at the end of a paper.

   Author's changes in manuscript:

   During the reworking of the manuscript, we will try to find a way to introduce a summary of hydrothermal alteration, metamorphism, and its relation to deformation earlier in the manuscript. For example, a summary paragraph could be included at the end of each relevant section to remind the reader of what was just presented and its significance. This should help the reader to stay with the overall narrative of the paper.

9. **Comment from referee:**

   Figures: Correct legend and check for completeness of all legends in all maps.

   Authors response:

   We note the problem with legends.

   Author's changes in manuscript:

   We will change the legends accordingly.

10. **Comment from referee:**

    Add legend to the stereographic plots.

    Authors response:

    The stereoplots do have legends inside the plot circle. We prefer to keep it this way because it saves a lot of space on the page.

    Author's changes in manuscript:

    We prefer to keep it this way because it saves a lot of space on the page and makes the stereo plot easier to read.

11. **Comment from referee:**

    Page 1, Line 16 ff.: Relationship between alteration assemblages is unclear. Why are there two regional hydrothermal alteration assemblages? What is their relationship? What is the importance of calcite? This needs explanation that is more careful and rewording.

    Authors response:

    According to the descriptive approach we have chosen in this manuscript, these mineral associations are to be considered as separate because they show overprinting relations to each other. However, we realize that these mineral associations may form part of an evolving hydrothermal system, which we state on page 12 line 10. The benefit of our approach is that it provides a scheme that is relatively easy to apply at the outcrop scale and does not lead to overinterpretation of how the hydrothermal systems evolved through time-space. We think this approach may be of some benefit to future geoscientists working in this area and also exploration geologists.

The relationship between the magnetite + amphibole and albite + scapolite alteration is that they are broadly coeval because they show crosscutting relationships to each other, which is stated on page 1, line 16.

The role of calcite is a very legitimate and good question and we thank JK for highlighting this. The simple answer is that we are uncertain about its role during either D1 or D2. However, calcite is present and we consider it important to describe in order to give a full view of the alteration minerals we have observed. One possibility, similar to that described by Kesler (2005), is that calcite formed at a relatively late stage of D1 and D2 during ingress of late fluid(s), facilitating the retrograde (down-welling) deposition of carbonate. The ultimate source of this carbonate would likely have been the supracrustal rocks which would have experienced some degree of decarbonation-devolatilization during regional metamorphism.

Author's changes in manuscript:

We will try to clarify the questions raised in this referee comment by explanation that is more concise and rewording of the relevant section.

12. **Comment from referee:**

Page 1, Line 20: Avoid the term “brittle-ductile”. This term is derived from geophysical (seismic) investigation of the Earth’s crust and defined as a zone of velocity change of seismic waves. It has no geological meaning. I can show you examples of brittle-ductile behaviour of rocks at 250◦C and at 650◦C. I suggest avoiding the term, because it does not add any information.

Authors response:

This is a good point. The term brittle-ductile is often used within structural geology to describe structures that contain both brittle and ductile components formed at the same time. This is also what we aim to describe by the term. As pointed out by JK, depending on many factors, such as mineralogy, strain rate, access to fluids etc., structures showing both brittle and ductile components form over a large temperature span. However, we believe use of this term adds geological information by emphasizing that a particular structure may show both brittle and ductile characteristics.

A few alternative terms could also be considered. The term “low grade” is one alternative frequently used. However, that term does not describe whether a structure contains only brittle- or only ductile-type deformation, or a mix of brittle and ductile structures.

Fossen (2010) defines plastic deformation as: …”the permanent change in shape or size of a body without fracture, produced by a sustained stress beyond the elastic limit of the material due to dislocation movement.” The term “brittle-plastic deformation” may here be the better term to use as it describes that crystal plastic deformation occurred as well as brittle deformation during the same deformation event (or stage). However, this term would still not bridge the dilemma on temperature since e. g. quartz and feldspar deforms by crystal-plastic deformation at different temperatures. The benefit of describing this from the WSB is that the presence of brittle components in the shear zones is a simple distinction between D1 and D2 structures. Brittle components have not been observed in structures that we interpret as D1-related whereas, brittle components have been observed together with ductile components in D2-structures.

Author's changes in manuscript:

We will change the term brittle-ductile to brittle-plastic in order to keep the description of brittle and ductile components formed together. We hope that our argumentation is valid on this point.

13. **Comment from referee:**

Page 2, Line 1: This sentence is misleading as is the referencing. The two papers do not describe the situation in Norbotten as your wording indicates. It is unclear to me, how metamorphic rocks with only restricted porosity (and generally no permeability) can focus fluid flow. Fluid follows the hydraulic gradient and can only migrate through permeable rock.

Authors response:

We agree that the references do not describe the situation in Norrbotten but addresses deformation and fluid flow from a fundamental point of view.

Author's changes in manuscript:

Text will be deleted in the resubmitted manuscript.

14. **Comment from referee:**

Page 2, Line 3 ff.: This is repeated from the previous page. Reword and avoid repetition.

Authors response:

We cannot find the repetition.

Author's changes in manuscript:

During the further reworking of the document we will see if we can locate what is addressed in this referee comment and reword in order to avoid repetition.

15. **Comment from referee:**

Page 2, Line 12: There is a problem here and also elsewhere in the text with the terminology. You define “Svekokarelian” as an orogeny. Here you use it as a stratigraphic term. This is confusing for the reader and needs to be avoided. In the regional geology chapter, a description of stratigraphy (old to young) and metamorphism and deformation (if information is available) is needed. The terminology needs to be clearly defined (if helpful with a table) and strictly used in the entire manuscript.

Authors response:

We agree that a figure explaining the stratigraphy of Norrbotten is needed for the manuscript. Such a figure will help clarify the confusion addressed by this referee comment.

However, even though the understanding of the timing of metamorphism and deformation has increased during the last 20 years of research, it is still relatively poorly understood. Nevertheless, including deformation and metamorphism in such a figure would be a beneficial summary of the geology in northern Norrbotten.

Author's changes in manuscript:

For the resubmitted manuscript, we will insert a figure explaining regional stratigraphy, metamorphism and deformation for Norrbotten.

16. **Comment from referee:**

Page 4, Line 25 ff.: What was used to constrain the PT conditions? The method or mineral assemblage needs to be stated. Otherwise, the reader cannot evaluate the quality of the data himself. Is it the metamorphic peak that is recorded? What is the approximate timing of metamorphism? You state that PT conditions raised from greenshist to amphibolite facies regionally, but then outline granulite facies conditions. What is true?

Authors response:

Bergman et al. (2001) does not go into to the details of this. The PT-conditions were based on mineral associations typical for the metamorphic zones. The mineral associations were supported by mineral chemistry obtained by microprobe. Most data comes from the high-grade areas.

The metamorphic evolution in northern Norrbotten is poorly constrained. Reset U-Pb ages indicate that there were at least two metamorphic peaks, M1 at approx. 1.9 Ga and M2 at approx. 1.8 Ga. However, the role of contact metamorphism etc. is an open question.

Granulite metamorphic facies has been recorded in volcanic rocks near 1.8 granites. This data probably reflects the influence of contact metamorphism.

Author's changes in manuscript:

“limited PT-modelling” has been changed to “microprobe data”.

The role and distribution of granulite facies metamorphism will be clarified in the text.

17. **Comment from referee:**

Page 4, Line 30 ff.: You say that the deformation is polyphase, but you only describe one stage of deformation in the text.

Authors response:

The text summarizes the literature that outlines at least two deformation events in N Norrbotten.

Author's changes in manuscript:

The paragraph will be reorganized and clarified in order to highlight D2 in a clearer way.

18. **Comment from referee:**

Page 10, Line 6: This needs much more explanation. How does dip-slip relate to compressional deformation? Generally, compressional deformation is related to folding, strike-slip and reverse shearing and not normal (dip-slip) deformation.

Authors response:

This referee comment points out the missing word “reverse” before “dip-slip” in this paragraph. We thank JK for pointing out this typing error. After adding “reverse” to the context, the sentence states that the relative movement of the shearing is “reverse dip-slip” that is the same as reverse shearing with the additional information that the movement occurred along the dip-direction of the plane.

Author's changes in manuscript:

This referee comment have been corrected for in accordance with the comment in the supplementary material “se-2019-150-RC2-supplement”.

We will check through the document in order to make sure that “dip-slip” is always stated “reverse dip-slip” since we have not observed structures showing normal dip-slip kinematics in this study.

19. **Comment from referee:**

Page 10, Line 10 ff.: You need to organize. E.g. you describe brittle and ductile deformation of feldspar, then describe many other things and then describe ductile deformation of quartz. See above; organize the structural description according to scale, either from small-scale to regional-scale or vice versa. The quartz fabrics (D1/D2 similar, low-T) contradict the feldspar fabrics (D1 >450◦C, D2 low-T) – why?

Authors response:

We agree that this passage in the text would benefit from a reorganization.

The question addressed by JK on the quartz textures is a very good question that we do not have a good explanation for at the moment. We will address this in the resubmitted manuscript based on our interpretation and literature context.

Author's changes in manuscript:

We will try to reorganize the text passage and try to address the contradiction of the quartz textures.

20. **Comment from referee:**

Page 12, Line 15 ff.: This remains unclear. If scapolite forms porphyroblasts, then it at least postdates D1 (otherwise, it must be porphyroclastic). If the veins are deformed by D2, then they predate D2. Which time constraints do you have between D1 and D2 to say that the veins postdate the scapolite porphyroblasts? Why is scapolite not formed at the same time?

Authors response:

The temporal relationship between porhyroblasts and deformation is described in detail by e. g. Passchier & Truow (2005). Porhyroblasts can form as pre- syn- or post-tectonism. Unfortunately, our thin section material from the WSB do not contain any scapolite porphyroblasts and thus we cannot show the timing of the scapolite porphyroblasts other than using our outcrop observations. However, we have studied scapolite porphyroblasts relative to deformation in thin section from the Pahtovaare- and Nunasvaara- areas east of the WSB. In both these places, the scapolite porphyroblasts show a syn- to post-timing (syn-D1 in Pahtovaare and syn-post-D1 in Nunasvaara) relative D1 and predate D2. However, because scapolite porhyroblasts constitute "rigid bodies" surrounded by weaker minerals they are not noticeably deformed by D2-deformation. We can provide images if there be of interest.

We agree that veins that are deformed by D2 must predate (or at least have been formed during) D2. We will carefully review and rework this passage in the text to make sure that our interpretations are consistent with our observations.

Author's changes in manuscript:

The timing of scapolite will be clarified in the text.

21. **Comment from referee:**

Page 13, Line 4 ff.: This is very confusing. You jump in your description from early to young and vice versa. The reader is unable to follow this. The important message is, which hydrothermal alteration assemblage(!) is temporally related to which structural fabric and to which stage in the metamorphic PT evolution (prograde, peak, retrograde). You also need to distinguish between hydrothermal alteration and metamorphic mineral assemblages. They form via completely different processes. This needs careful rewording.

Authors response:

We agree that this paragraph describing epidote in different mineral associations is confusing and could be more clearly structured.

Author's changes in manuscript:

We will rearrange this paragraph, or possibly delete it and move parts of this text to other paragraphs describing mineral associations where epidote is a component mineral.

22. **Comment from referee:**

Page 14, Line 20 ff.: What about the feldspar microstructures described above? What do they indicate? What about the mineral assemblages? Which PT conditions do they indicate? This needs much more discussion and integration of microstructural and petrological data. Likely much better PT constrains are possible by such an integration.

Authors response:

This is a good point.

The feldspar microstructures indicate that the temperatures were lower during D2 in respect to D1 because brittle feldspar is only observed in E-W-trending D2-structures.

Author's changes in manuscript:

We will try to develop this in the resubmitted manuscript.

23. **Comment from referee:**

Page 15, Line 5: Relatively low P and upper crustal conditions are also true for D1 deformation. This does not add any information and is a very vague and imprecise statement. See also comment above.

Authors response:

It is true that both D1 and D2 are rather low grade, however, observations of D2 structures indicate that the deformation took place higher up in the crust in respect to D1. We believe that this is rather well described for D2 but the manuscript probably requires a better description for D1 and what is indicated in these D1-structures with respect to inferred P-T conditions.

Author's changes in manuscript:

We will try to address an estimation about inferred P-T conditions for D1-structures.

24. **Comment from referee:**

Page 15, Line 6 ff.: This needs more discussion. It remains completely unclear, why you add information from other localities and which relevance that may have. You first need to constrain PT conditions and relative timing of deformation, metamorphic and hydrothermal stages in your study area before you can compare those to other (similar or connected) areas. Readers, who are not familiar with the regional geology, will be confused and cannot decide on the relevance of the data presented here for comparison.

Authors response:

The relevance of comparing results from nearby areas to our observations in the WSB is that it is important to highlight what observations agree with the current understanding of the northern Norrbotten area. We think that such comparisons are important also from areas that are not fully understood (e. g. the WSB). We do not consider this study will be the last on the WSB, but we rather hope it represents an initial study to build further upon by future work.

Author's changes in manuscript:

We will clarify in the text the importance of comparing the results in this study to results from adjacent areas and place an emphasis on our results and interpretations and how they then may relate to other localities (if needed).

25. **Comment from referee:**

Page 15, Line 13 ff.: This part suffers from bad wording and poor organization. Please reword and discuss from old (L1) to young (L2). The mineral species that define the stretching lineation may help in constraining relative timing and PT conditions.

Authors response:

The beginning of the paragraph is described from old (L1) to young (L2). The end of the paragraph discusses why L1 and L2 can be separated and that they are best explained by different shortening directions. We agree that the end of the paragraph may be improved by reorganization and rewording or by making two paragraphs of this long paragraph.

Author's changes in manuscript:

The paragraph on page 15 including line 13 will be carefully reviewed and reorganized in the resubmitted manuscript.

26. **Comment from referee:**

Page 16, Line 20 ff.: Why are you presenting this? There is a lot of speculation and the reader gets no idea, what the relevance of this is: delete.

Authors response:

The reason why this discussion was presented in the manuscript is that there is a paradox in the interpretations on the tectonic setting for the earliest deformation history in northern Norrbotten. Studies based on structural geology tend to argue for a compressional setting and the development of a fold-and-thrust belt. In contrast, studies based on petrology tend to argue for an extensional setting (back-arc or mantle plume). We think that it is relevant to compare structural results to petrological results in order to discuss the overall tectonic setting in the area. But it is possible that we can do that in a much clearer way or in other parts of the manuscript.

Author's changes in manuscript:

We will clarify this, either, by deleting this text or by moving parts of the text to other paragraphs.

27. **Comment from referee:**

Page 16, Line 26 ff.: I am confused: Why do D2 shear bands indicate D1 deformation?

Authors response:

Because there is an overprinting relationship. Due to the presence of D2-shearbands that deform the S1-fabric, we interpret the S1-fabric to be D1-related and the overprinting shear band as a D2-related structure.

Author's changes in manuscript:

We will try to clarify this in the resubmitted manuscript.

28. **Comment from referee:**

Page 17, Line 2 ff.: What is the timing of metamorphism? The epidote-amphibolite facies in pillow basalts can be very early in the evolution and may represent seafloor metasomatism. Alternatively, a similar mineral assemblage can form during regional metamorphism. This needs more discussion of evidence of relative timing.

Authors response:

This is a valid question. We will present evidence for syn-D1 growth of hornblende in the same sample as shown in Figure 15 G in order to clarify the timing of M1 (this will not be Fig. 15G anymore after inserting the figure on the stratigraphy in northern Norrbotten in accordance with earlier referee comments).

Author's changes in manuscript:

We will add a figure in fig. 15. We may be forced to delete one image from Fig. 15 in order to make room for this new micrograph. We will take a discussion about this and possibly consult the editor in how we solve this issue.

29. Comment from referee:

Page 19, Line 4: If the scapolite is really porphyroblastic everywhere, then it must (by definition) be post-tectonic. You say that the scapolite porphyroblasts occur in low-strain areas, which may mean that scapolite growth postdates D1 here but is pre-, syn- or post-D1 in the high-strain zones. This needs more discussion and more precise investigation of the relative timing. Furthermore, you contradict yourself with the interpretation of the absolute age data. You say that D1 is 1.88-1.86 Ga, that scapolite alteration is syn- to late-D1 and that scapolite formed (together with titanite) at 1.9 Ga. This is 20-40 m.y. earlier than D1 and not syn- to late-D1. Moreover, you do not provide the precision of the geochronological data, which makes further evaluation by the reader impossible. Is scapolite formed during seafloor alteration at 1.9 Ga?

Authors response:

For the comment on scapolite porhyroblasts, see our response on the referee comment regarding Page 12, Line 15 ff. We agree on that that the timing of scapolite porhyroblasts can be clarified further in the text.

The age obtained by Smith et al. (2009) is reported at 1903±8 Ma.

JK points out important weaknesses in the understanding of the early scapolitization in northern Norrbotten. This question deserves attention and his comment highlights the need for further geochronological data on scapolite-altered rocks in Norrbotten. Scapolite has never been studied from a structural geology perspective in Norrbotten, hence, we hope that our field observations can add information to the overall picture.

Author's changes in manuscript:

We will reconsider to draw any parallels between scapolite porhyroblasts in the WSB and the titanite age of a scapolite-altered mineral association reported by Smith et al. (2009).

30. Comment from referee:

Page 19, Line 10 ff.: The discussion about Cl/Br geochemistry and fluid source remains unclear. If you have two generations of scapolite, what will whole rock data tell you? Why do you consider an evaporitic source, when the data contradicts this? This needs much more discussion, if this is important for the conclusions of this work. I am not sure, where this will lead to?? You don't really have shown constrains on the relative timing of scapolite alteration. This makes it really difficult to follow.

Authors response:

We have reworded this passage while working through the comments in the supplementary material "se-2019-150-RC2-supplement". However, we find this text targeted by this referee comment as slightly out of scope for this study and the text is probably not needed. Thank you for pointing this out.

Author's changes in manuscript:

This text will be deleted in the resubmitted manuscript.

31. **Comment from referee:**

Page 19, Line 17 ff.: If you would follow the geological principle of describing the oldest features first, your text would be much easier to follow. You get not all possible information out of your data. There is much more on P-T-D-X relationships in your data that needs to be presented and discussed. The important part is that hydrothermal alteration assemblages are controlled by complex P-T-X relationships. The mineral presence in the hydrothermal alteration assemblages depends not only on fluid composition, but also on host rock composition and fluid rock ratio. Thus, it is very common in hydrothermally altered regions to find different hydrothermal alteration assemblages in different host rocks that formed at the same time or to find zoning of hydrothermal alteration assemblages depending on the distance from the main hydrothermal fluid conduit (e.g. a shear zone or a pluton). All this needs to be worked out from your data and displayed in maps and discussed accordingly.

Authors response:

We agree with JK that there is probably much more to the P-T-D-X relationships in WSB than is shown by this study. We agree that this constitutes a very interesting question and deserves further attention from the research community. However, we consider a thorough thermodynamic investigation of the mineral alteration systems in the WSB as the next step to take in the geological research in the area. Such a study would require a different approach than what we have chosen in this study. In this study, we present geological mapping results performed during three field seasons (May-October) which forms a part of the lead authors ongoing PhD research (see Andersson et al. 2017, Andersson 2019, Andersson et al. 2019). Our observations are backed up by a petrographical investigation focused on kinematics of the dominant structures and linked to the mineral alteration associations that we have observed throughout the belt. We find the suggested work to be beyond scope for the current study but we encourage further work on the complex questions addressed by this referee comment.

Author's changes in manuscript:

As mentioned in comments to previous referee comments, we will make sure that our descriptions and/or discussions follow the overall structure old-to-young. We agree on that this makes sense. However, in some cases different generations may need to be alternatively described in relation to each other in the same sentence in order to make the context as clear as possible.

In the resubmitted manuscript, a mineral alteration map will be included. However, it is important to note that this map will carry uncertainties that must be considered as high. We will try to communicate this as clear as possible in the resubmitted manuscript.

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Evolution of structures and hydrothermal alteration in a ~~Palaeoproterozoic metasupracrustal~~Paleoproterozoic supracrustal belt: Constraining paired deformation-fluid flow events in ~~a~~an Fe and Cu-Au prospective terrain in northern Sweden

Joel B. H. Andersson[1], Tobias E. Bauer[1], Edward P. Lynch[2]

[1]Division of Geosciences and Environmental Engineering, Luleå University of Technology, SE 971 87 Luleå, Sweden
[2]Department of Mineral Resources, Geological Survey of Sweden, Box 670, SE 751 28, Uppsala, Sweden.

Correspondence to: Joel B. H. Andersson (joel.bh.andersson@ltu.se)

Abstract. ~~In this field-based study, a ~~~An approximately 90 km~~-~~-long ~~Palaeoproterozoic metasupracrustal~~Paleoproterozoic supracrustal belt in the northwestern ~~part of the~~ Norrbotten ore province (northernmost Sweden) ~~has been~~was investigated ~~in order~~ to characterize its ~~various~~ structural components, assess hydrothermal alteration-structural geology correlations, and ~~thus~~ constrain ~~its structural evolution. In addition, hydrothermal mineral associations are described and linked to identified~~a paired deformation ~~phases~~-fluid flow evolution for the belt. New geological mapping of five key areas (Eustiljåkk, Ekströmsberg, Tjårrojåkka, Kaitum West and Fjällåsen-Allavaara) indicates two major compressional events (D_1~~,~~ and D_2) ~~that~~have affected the belt ~~whereas~~, with each ~~deformation event can be related to specific~~associated with hydrothermal alteration ~~styles~~types typical for iron oxide-apatite and iron oxide Cu-Au systems~~.~~ in the region. Early D_1 generated a regionally distributed, penetrative S_1 foliation and oblique reverse shear zones ~~with~~that show a southwest block up sense-of-~~shears~~ shear that formed in response to NE-SW crustal shortening. Peak regional metamorphism at epidote-amphibolite facies broadly overlaps with this D_1 event. Based on overprinting relationships, D_1 is associated with regional scapolite ± albite ~~alteration formed coeval with regional~~, magnetite ~~±~~+ amphibole ~~alteration~~, and late calcite ~~under epidote-amphibolite metamorphism.~~ alteration of mafic rock types. These hydrothermal mineral associations linked to D_1 structures may form part of a regionally pervasive evolving fluid flow event but are separated in this study by crosscutting relationships.

During D_2 deformation, folding of S_0-S_1 structures generated F_2 folds with steeply ~~south~~ plunging ~~F_2 folds~~fold axes in low strain areas ~~whereas most strain was partitioned into pre-existing~~. NNW-trending D_1 shear zones ~~resulting in~~experienced reverse dip-slip reactivation ~~of steep NNW-oriented D_1 shear zones~~ and strike-slip dominated movements along steep, E-W-trending D_2 shear zones ~~under~~producing brittle-~~ductile conditions. The hydrothermal~~plastic structures. Hydrothermal alteration linked to ~~the~~ D_2 ~~deformation phase~~structures is ~~more~~a predominantly potassic ~~in character and dominated by~~ ferroan association comprising K-feldspar ± epidote ± quartz ± biotite ± magnetite ± sericite ± ~~sulphides, and~~sulfides. Locally, syn- or post-tectonic calcite~~.~~ is the main alteration mineral in D_2-shear zones that intersect mafic rocks. Our results ~~underline~~highlight the importance of ~~paired~~combining structural ~~alteration approaches at the~~ geology with the study of hydrothermal alterations at regional- to belt-~~scale~~scales to understand the temporal-spatial relationship between mineralized systems. Based on the

mapping results and microstructural investigations, as well as a review of earlier tectonic models presented for adjacent areas, we suggest a new structural model for this part of the northern Fennoscandian Shield. OurThe new structural model emphasizes the importance of reactivation of early structures and the model harmonizes with earlier petrological/geochemical tectonic models presented by earlier workers based mainly on petrology of the northern Norrbotten area and emphasizes the importance of reactivation of early formed structures.

1 Introduction

The northern Norrbotten orearea of Sweden is an economically important metallogenic province in northern Sweden represents one of Europe's key and mining and exploration areas.district (Weihed et al. 2008). For example, about 90% of European iron ore is annually produced in the area from two of the world's largest underground iron mines at Kiirunavaara and Malmberget. (LKAB, 2017; OECD, 2017). These world-class deposits (combined current reserves of c. 1051 Mt @ 43.4% Fe; Loussavaara-Kiirunavaara ABLKAB, 2017) comprise iron oxide-apatite (IOA) or "Kiruna-type" mineralization, with the formerKiirunavaara deposit representing the archetypal example (e.g. Geijer, 1910; 1930). The Aitik Cu-Ag-Au deposit also occurs in northern Norrbotten and is one of the largest open-pit copper mines in Europe (current resource of c. 801 Mt @ 0.22 % Cu, 1.3 g/t Ag and 0.15 g/t Au; (New Boliden AB, 2017). Aitik represents an enigmatic porphyry-style deposit with a protracted ore- forming history that is thought to include an overprinting iron oxide-copper-gold (IOCG)-style mineralization event (e.g. Wanhainen et al., 2005; 2012). Beyond the active mines, numerous Fe and Cu ± Au prospects and deposits occur, making the area one of the most prospective terrains in Europe for IOA- and IOCG-style mineralizationdeposits (e.g. Carlon, 2000; Billström et al., 2010; Martinsson et al., 2016).

In northern Norrbotten (Fig.1), Paleoproterozoic volcanic-sedimentary successions mainly occur within approximately NNW- to NNE-trending metasupracrustal belts (e.g. Bergman et al.,Paleoproterozoic supracrustal belts in Norrbotten are 2001). Although volumetrically minor, these belts are significant because their contained lithotypes and structures provide evidence for the long-lived tectonothermal evolution of this sector of the Fennoscandian (Baltic) Shield (Fig. 1). For example, Rhyacian (c. 2.2 - 2.1 Ga) greenstone sequences record a phase of continental rifting, basin formation, mafic-ultramafic magmatism and sedimentation during extensional tectonism (Gustafsson, 1993; Martinsson, 1997; Melezhik and Fallick, 2010; Lynch et al., 2018a). In contrast, younger Orosirian (c. 1.9 – 1.8 Ga) volcanic and sedimentary rocks provide insights into subduction-related magmatism, regional metamorphism and accretionary-collisional processes during the Svecokarelian (or Svecofennian) orogeny (Skiöld et al., 1988; Öhlander et al., 1999; Bergman et al., 2006; Lahtinen et al., 2015). This phase of convergent tectonism promoted basin inversion and juxtaposed supracrustal rocks of differing character and provenance within several discontinuous, curvilinear metasupracrustal domains that are typically bounded by more aerially extensive syn- to late-orogenic intrusions (Pharaoh and Brewer, 1990; Ahl et al., 2001; Bergman et al., 2001; Sarlus et al., 2017; Luth et al., 2018).

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~~Paleoproterozoic metasupracrustal belts in Norrbotten are also~~ significant from a metallogenic perspective as they preferentially host a variety of base and precious metal ~~mineralization,~~ores and thus represent key exploration targets (e.g. Carlon, 2000; Martinsson, 2004). In detail, syn-orogenic 'Svecofennian' sequences deposited between c. 1.90 – 1.87 Ga represent a key ~~metalliferous~~stratigraphic horizon that locally hosts significant IOA- and IOCG-style ~~mineralization~~deposits (Romer et al., 1994; Edfelt et al., 2005; Smith et al., 2007; Wanhainen et al., 2012; Westhues et al., 2016). ~~Deposits of both~~Both deposit types commonly occur within or immediately adjacent to ~~major ductile-brittle~~ large-scale deformation zones, which ~~tend to~~ traverse and follow the ~~metasupracrustal~~supracrustal belts, suggesting these ~~domains~~zones and their ~~constituent~~contained lithologies strongly influenced strain localization. ~~Norrbotten~~

Paleoproterozoic ~~metasupracrustal~~supracrustal rocks in northern Norrbotten also preserve evidence of ~~both~~ regional- and local-scale ~~metasomatic~~ hydrothermal alteration and fluid-rock interaction (e.g. Romer, 1996; Frietsch et al., 1997; Edfelt et al., 2005; Bernal et al., 2017), and share broad lithological, structural and alteration characteristics with other IOCG- and IOA-prospective terrains worldwide. For example, features such as variably distributed sodic and potassic alteration, the bimodal character of host volcanic rocks, the spatial proximity of deformation zones and Cu-Au mineralization conform with the IOCG mineral system model defined by Skirrow et al. (2019), and mimic the character of other IOCG-mineralized terrains in Brazil (e.g. deMelo et al., 2017; Craveiro et al., 2019), Australia (e.g. Skirrow et al., 2019), Canada (e. g. Corriveau and Mumin, 2010; Corriveau et al., ~~). This characteristic affirms the efficiency of these rock sequences and their associated structures to channel and focus the flow of potential metal-bearing fluids through the supracrustal pile (cf. Oliver and Bons, 2001; Cox, 2005).~~2016) and Mauritania (e.g. Kolb et al., 2008). Therefore, further studies of IOA- and IOCG-prospective terrains in northern Sweden may contribute to an improved understanding of the formation of these deposit types, provide new insights into the broader controls on mineralization, and help refine conceptual ore-forming or exploration models applicable to geographically isolated and underexplored supracrustal domains in northern Fennoscandia, or analogous terrains elsewhere.

~~Previous studies of Svecokarelian-cycle metasupracrustal~~The deposition of Orosirian supracrustal rocks, collectively referred to as 'Svecofennian' (e.g. Gaal and Gorbatschev, 1987), marks the onset of the Paleoproterozoic Svecokarelian orogeny (c. 1.96-1.75 Ga) in Sweden. Previous studies of Svecofennian supracrustal rocks in northern Norrbotten have included provincial compilations to ascertain lithostratigraphic and petrogenetic insights (e.g. ~~Freitsch~~Frietsch, 1984; Pharoh and Pearce, 1984; Forsell, 1987; Perdahl and ~~Freitsch~~Frietsch, 1993; Bergman et al., 2001), and local studies constraining the geological, geochemical, geophysical and/or structural character of sequences hosting Fe and Cu ± Au deposits (e.g. Geijer, 1910; 1920; 1930; 1950; Parak, 1975; Edfelt et al., 2006; Sandrin and Elming, 2006; Smith et al., 2007; Wanhainen et al., 2012; Westhues et al., 2016; 2017; Bauer et al., 2018). With a few exceptions (~~cf.~~ Wright, 1988; Bergman et al., 2001; Grigull et al., 2018, Lynch et al. 2018), regional compilations have ~~lacked accompanying~~tended to lack structural information. Local studies with a structural component (e.g. ~~Debras, 2010;~~ Edfelt et al., 2006; Debras, 2010; Wanhainen et al., 2012) ~~have~~ generally did not ~~considered~~consider the broader significance of deposit-proximal structures in reconstructing deformation and/or fluid~~-~~-flow events for individual belts or the wider region. Thus, deformation zone- or belt-scale investigations ~~of Svecokarelian-related metasupracrustal rocks~~ that include a coupled structural-alteration assessment may provide new insights

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into the number and character of paired deformation-hydrothermal events affecting a particular belt, with the potential to extrapolate broader tectonothermal implications. This approach may also help identify new geological vectors to IOA and/or IOCG mineralization applicable to underexplored and geographically isolated metasupracrustal domains in Norrbotten, or analogous terranes elsewhere (cfgiven supracrustal belt., Corriveau and Mumin, 2010; Corriveau et al., 2016).

In this paper, we present a predominantly field-based investigationnew structural and alteration mapping of ana deformed and metamorphosed Orosirian metasupracrustalsupracrustal belt located about 40 km to the west of Kiruna in northwest Norrbotten, northern Sweden (Figs. 1, 2 and 3). The studied sequence, herein referred to as the Western Supracrustal Belt (cf. Wright, 1988 – see Section 3 below), extends for about 90 km in a NNW-SSE direction and overlaps with the location of a major ductile-brittle deformation zone that hosts several Fe and Cu ± Au occurrences (e.g. Offerberg, 1967; Witschard, 1975; Edfelt et al., 2005; Frietsch, 1974; Wright, 1988; Lynch et al., 2014).). New geological mapping of five key domains is used to ascertain the types, geometriestype, geometry, kinematics and interrelationships of various structural components within the belt, and thus constrain its structural evolution. Additionally, a petrographic and paragenetic assessmentstudy of mappable hydrothermal alteration zones associated with different lithotypes and/or structures is used to constrain the character and number of fluid-flow events within the metasupracrustalsupracrustal rocks, and attempts to link these hydrothermal events to specific phases of deformation. Overall, this coupled structural-alteration approach aims to developprovides a new unifying deformation model for the investigated belt, identifyWestern Supracrustal Belt, identifies key structural controls on hydrothermal alteration (and by inference Fe and Cu ± Au mineralization),) and, to establish a new establishes an updated space-time framework for Svecokarelian cycle deformation and hydrothermal fluid- -flow in this sector of northern Fennoscandia.

For simplicity, the prefix "meta" for various metamorphic rocks (e.g. metarhyolite) is not used in this paper as all rocks have been metamorphosed to some degree (Bergman et al. 2001). We also follow the recommendations of the Committee for Swedish Stratigraphic Nomenclature for geological and stratigraphic naming conventions (Kumpulainen 2007).

2 Regional geological setting

The northern part of the Fennoscandian Shield (Fig. 1) is underlain by a continental nucleus of Archean (c. 2.9-2.6 Ga) granitic, tonalitic and amphibolitic gneisses (Gaal and Gorbatschev, 1987; Weihed et al., 2005). In northern Sweden, Archean rocks belong to the Norrbotten Craton, one of three continental nuclei that were dispersed and reassembled during a 'Wilson-style' rifting and accretionary-collisional cycle in the Paleoproterozoic (e.g. Lahtinen et al., 2005). Continental rifting and dispersal2008). Rifting of this continental basement between c. 2.5 and 2.1 Ga developed crustal-scale, rift-parallel fault systems and basins, and voluminous tholeiitic mafic magmatism, and associatedrelated sedimentation which form a major, producing an approximately NW-aligned large igneous province extending NW-SE from northern Norway to Russia (Pharaoh and Pearce, 1984; Hanski, 2012; Melezhik and Hanski, 2012; Hanski et al., 2014; Bingen et al., 2015). In northern Sweden, Archean rocks belong to the Norrbotten Craton, one of three continental nuclei that were rifted during the Rhyacian and later

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Formatted: Indent: First line: 0,5 cm reassembled during the Svecokarelian accretionary-collisional orogenic cycle in the Orosirian (e.g. Lahtinen et al., ~~,~~2005; 2008). In northern Norrbotten (Fig. 1), Rhyacian rift ~~basins~~basalt and related mafic igneous and sedimentary rocks constitute the lowermost part of the Paleoproterozoic stratigraphy (Fig. 4) and occur within several NNE- and NNW-trending greenstone belts (e.g. Martinsson, 1997; Melezhik and Fallick, 2010; Lynch et al., 2018a).

Early Svecokarelian-cycle orogenic magmatism (c. 1.90-1.86 Ga) in northern Sweden generated two regional suites of co-magmatic ~~volcanic~~volcano-plutonic rocks that are ~~broadly~~ divisible based on petrological, geochemical and geographical considerations~~.~~ (Fig. 4). In the east, calc-alkaline ~~series~~ intermediate to felsic volcanic-volcanoclastic rocks and co-magmatic dioritic to granodioritic intrusions predominate (i.e. Porphyrite group and Haparanda intrusive ~~suite of Bergman et al., 2001, respectively).~~suites in Figure 4). In the west, mildly alkaline (shoshonitic), intermediate to felsic volcanic-volcanoclastic rocks and co-magmatic monzonitic intrusions occur (i.e. ~~Porphyry~~Kiirunavaara group and Perthtite Monzonite intrusive ~~suite of Bergman et al., 2001).~~suites in Figure 4). Late Svecokarelian-cycle magmatism ~~from 1.81-1.65 Ga, during a possible phase of eastward subduction,~~in northern Norrbotten generated ~~wide spread~~ widespread c. 1.81-1.78 Ga, I- to A-type granitic plutonism (Edefors suite in Figure 4) and coeval S-type granites ~~from northern Norway~~(Lina suite in Figure 4) in response to ~~southern Sweden~~eastward subduction as part of the Transcandinavian Igneous Belt (Andersson, 1991; Åhäll and Larson, 2000; Weihed et al., 2002; Högdahl et al., 2004; Rutanen and Andersson, 2009).

In general, metamorphic facies and related pressure-temperature (P-T) estimates are poorly constrained throughout northern Norrbotten (e.g. Bergman et al. 2001, Skelton et al., 2018~~). However, based~~) but at least two regional metamorphic events (Fig. 4) that broadly correspond to the early- and late-orogenic cycles are reported (Bergman et al., 2001; Bergman et al., 2006; Bergman, 2018; Sarlus et al., 2018). Based on metamorphic mineral ~~assemblages~~associations and ~~limited P-T modelling~~microprobe data, Bergman et al. (2001) suggested that the regional metamorphic grade increases from ~~greenshist~~greenschist to amphibolite facies conditions ~~going~~ from west to east. East of the Western Supracrustal Belt (Fjällåsen; Fig. 1, 2, 3), syn-orogenic ~~metavolcanic~~volcanic rocks ~~have~~ yielded P-T values of 4.0 – 7.5 ~~kbars~~kbar and 630° - 805°C, respectively (i.e. amphibolite to granulite facies; Bergman et al~~.,~~. 2001). The uppermost granulite facies P-T estimate (7.5 kbar/805°C) was determined for a sedimentary rock within a high-strain deformation zone and bounded by c. 1.8 Ga granites, and may represent contact metamorphic conditions around the granite plutons and/or the effects of retrograde reactions (Bergman et al., 2001).

~~2001).~~ In the Gällivare area (Fig. 1), shear zone-hosted ~~(mylonitic)~~ schists along the Nautanen Deformation Zone have yielded P-T values of 2.5 – 4.3 ~~kbars~~kbar and ~~c.~~ 589 – 681°C~~, respectively~~ (i.e. amphibolite ~~to granulite~~ facies; Tollefsen, 2014). Also in the Gällivare area, Romer (1996) reported a U-Pb ~~ages at~~age of 1730 ± 6.4 Ma for fracture-hosted stilbite in ~~metavolcanic~~volcanic rocks, suggesting ~~the~~this area has remained below the closure temperature of stilbite (c. 150°~~-~~C) since c. 1.73 Ga. A possible regional resetting of the Rb-Sr isotopic systems at c. 1.6-1.5 Ga (e.g. Welin, et al., 1971; Skiöld, 1979) is recorded by c. 1.9 – 1.8 Ga magmatic rocks in northern Norrbotten (Fig. 4). ~~then~~In central Sweden, c. 1.6 – 1.5 Ga rapakivi intrusions occur (Andersson, 1991; Andersson, et al., 2002) but magmatic and/or hydrothermal ages in Norrbotten are not known during this time-span, hence, the geological significance of the isotope resetting remains unclear.

Paleoproterozoic rocks in northern Norrbotten record evidence of a complex, polyphase deformation history that evolved predominantly in response to Svecokarelian~~-related orogenic~~ orogenesis (D_1 and D_2 in Fig. 4) and involves at least two regional deformation events (e.g. Vollmer et al., 1984; Forsell, 1987; Wright, 1988; Bergman et al., 2001; Bauer et al., 2018; Grigull et al., 2018; Luth et al., 2018, Andersson, 2019). In the Kiruna area, Wright (1988) argued for an early D_1 thrusting event overprinted by gentle, local folding and shear zone development~~.~~ (D_1 to D_4 in Wright 1988). For the same area, Andersson (2019) ascribed the earliest Svecokarelian compressional deformation to basin-inversion and proposed four major deformation phases to explain the structural configuration in the Kiruna area (D_1-D_4 in Fig. 4). Bergman et al. (2001) ~~reported~~argued for two regional ~~deformational~~deformation events (D_1 and D_2) in northern Norrbotten and Bauer et al. (2018) ~~showed~~described a ~~higher-grade deformation event overprinted~~pronounced gneissic S_1 cleavage affected by ~~lower-grade~~F_2 folding in the Gällivare area~~.~~ (Fig. 1) implying two deformation events.

The ~~timing~~maximum age of the ~~early tectonothermal event has been suggested to 1.90-1.88 Ga~~earliest D_1 event in Kiruna is constrained at 1880 ± 3 Ma by Cliff et al. (1990) based on a zircon U-Pb TIMS age for an undeformed granophyre dyke cutting the Kiirunavaara IOA deposit~~ interpreted to represent the maximum age of the deformation.~~. A similar timing ~~of the same event~~for D_1 has been inferred based on deformation ~~styles~~intensity recorded by ~~ca~~c. 1.89 – 1.88 Ga as well as 1.88 – 1.86 Ga plutonic rocks in northern Norrbotten (Bergman et al., 2001). The timing of the ~~later~~regional D_2 tectonic event is generally constrained by the emplacement of ~~ca~~syn- to late-orogenic c. 1.8 Ga ~~granitic intrusions~~granites and related hydrothermal activity (e.g. Bergman et al., 2001; Smith et al., 2009; Bauer et al., 2018). The D_4-event in Figure 4 corresponds to maximum ages of c. 1740 Ma and 1620 Ma for open fractures in the Gällivare area (Romer, 1996) and is the last documented Proterozoic deformation in that area (Bauer et al. 2018).

3 Geology of the Western Supracrustal Belt

3.1 Setting, extent, and lithotypes

The Western Supracrustal Belt (WSB) refers to a discontinuous, c. 6 km-wide by 90 km-long, NNW-trending Orosirian (c. 1.89 – 1.87 Ga)~~ lithotectonic~~ domain located to the west of Kiruna in northwestern Norrbotten (Fig. 2, 3). In an earlier study, Wright (1988) defined the WSB as a north-south trending supracrustal inlier zone immediately to the west of Kiruna (i.e. the Eustiljåkk key area: Fig. 2, 3). However, this area represents the northernmost part of a ~~much~~ larger supracrustal terrain that extends further southward to the west and southwest of the Kiruna and Gällivare mining areas. In this study, we retain the original nomenclature of Wright (1988) but expand the term "Western Supracrustal Belt" to include the areas from Allavaara-Fjällåsen in the south to Eustiljåkk in the north that are underlain by Orosirian ~~metasupracrustal~~supracrustal rocks (Fig. 2, 3). Similar lithostratigraphic domains occur to the west of the WSB as relatively small ~~inlier "windows"~~inliers surrounded by Paleoproterozoic plutonic rocks or ~~younger (~~as tectonic windows surrounded by Paleozoic~~) Caledonian cycle~~ rocks (e.g. Angvik, 2014).

In general, the geology of the WSB is dominated by calc-alkaline to alkaline, volcanic-~~volcaniclastic~~volcanoclastic rocks with basaltic to rhyolitic compositions that were metamorphosed ~~to~~at approximately peak epidote-amphibolite facies conditions (Ros, 1979; Bergman et al., 2001; Edfelt et al., 2006). Along its margins, the WSB is ~~bounded~~bound by subordinate, c. 1.88-1.86 Ga granodiroritic to dioritic plutonic rocks and more abundant c. 1.80 Ga ~~granitoids~~granites (Bergman et al., 2001). The plutons intrude, truncate and disrupt the supracrustal pile and this aspect, combined with the polydeformed nature of the sequence ~~(see below),~~, makes lateral stratigraphic correlations difficult. In the Ekströmsberg area (Fig. 2, 3), Rhyacian greenstones are found at the margin of the belt providing a partly persevered pre- to syn-orogenic stratigraphic record (Offerberg, 1967; Witschard, 1975a). In the Allavaara area (Fig. 2, 3), Witchard (1975a) ~~also~~ indicated synclinal folds comprised ~~of~~ Rhyacian greenstones on their flanks ~~cored by~~and Orosirian felsic to intermediate volcanic rocks in their cores.

3.2 Structural geology

Previous studies incorporating parts of the WSB ~~have provided an intermittent~~provide a partial and somewhat contradictory assessment of its structural character and evolution (c.f. Wright, 1988; Bergman et al., 2001; Edfelt et al., 2006). ~~In the~~At Eustiljåkk ~~area~~in the northern WSB (named *Ruojtatjåkka South* in Wright, 1988~~) in the north,~~), Wright (1988) identified a steep, NW-trending mylonite zone that mimics the NNW-orientations of high-strain zones at Allavaara ~~in~~to the south (Fig. 2, 3). The Eustiljåkk mylonite ~~provided~~provides kinematic evidence for a west-side-down, oblique normal sense-of-shear, based on rotated porphyroclasts with asymmetric tails (Wright, 1988). In contrast, Bergman et al. (2001) ~~reported~~report overall west-side-up kinematics for the composite shear zone within the WSB based on outcrop observations west of Kiruna and Gällivare (Fig. 1). A set of ENE-trending dextral strike-slip shear zones in the Eustiljåkk area (*Ruojtatjåkka South* in Wright, 1988) have also been reported by Wright (1988~~)~~), who suggested these structures post-date the dominant NNW-SSE tectonic grain.

Based on airborne (Bergman et al., 2001) and ground magnetic data (Frietsch et al., 1974), several prominent NNW-trending linear magnetic anomalies occur along the WSB, or as splay anomalies extending NW to WNW ~~toward~~towards the Tjårrojåkka area (Fig. 3). These ~~magnetic~~ lineaments ~~have generally been~~are assigned to an unnamed, crustal-scale Paleoproterozoic shear zone, analogous to the major NE-trending Karesuando-Arjplog Deformation Zone to the northeast and the NNW-trending Nautanen Deformation Zone to the east (e.g. Bergman et al., 2001; Sandrin and Elming, 2006). Moreover, the magnetically anomalous character of the WSB mimics similar "striped" magnetic signatures associated with intense magnetite alteration and mylonitic deformation within the better understood IOCG-mineralized Nautanen Deformation Zone ~~near Gällivare~~ to the east (Fig. 1; e.g. Lynch et al., 2015; Lynch et al., 2018b~~).~~) giving relevance to regional comparisons.

3.3 Mineralization and related alteration

Both iron oxide-apatite (IOA) and hydrothermal Cu ± Au mineralization ~~occur~~occurs along the WSB. The best documented examples are the Tjårrojåkka Fe-Cu system (e. g. Edfelt et al. 2005, 2006) in the ~~southwest~~west and the Ekströmsberg IOA deposit (Frietsch, 1974) in the ~~north~~east (Fig. 2, 3). The Tjårrojåkka system (Edfelt et al., 2005, 2006) comprises a western IOA deposit and an IOCG-style Cu ± Au ore body in the east. The IOA deposit is primarily associated with pervasive albite +

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scapolite + magnetite ± amphibole alteration, while “red rock”-style potassic-ferroan (K-feldspar + hematite ± albite) alteration is mainly associated with the Cu deposit (Edfelt et al., ~~2006~~2005). The Ekströmsberg deposit comprises several parallel, NW-trending magnetite and hematite ~~ore bodies~~orebodies. The ~~ore bodies~~orebodies are associated ~~to~~with sericite + quartz-altered host volcanic rocks and discordant calcite veining, as well as muscovite, zircon, epidote, tourmaline and allanite as probable secondary accessory matrix minerals (Frietsch, 1974).

In general, ~~the siting of~~ Fe and Cu mineralization along the WSB appears to be partly controlled by superimposed structures formed during polyphase deformation. In the Tjårrojåkka area, Edfelt et al. (2006) ~~reported~~report three ~~deformational~~main deformation events; D_1 and D_2 ~~which~~ generated cleavages in NE- and E-oriented shear zones, respectively, and a later D_3 event ~~which~~ folded D_1 structures and produced shallow SE-striking cleavages dipping towards the southwest. Additionally, the Fe and Cu ore bodies at Tjårrojåkka are aligned with D_1~~-related~~ NE- to ENE-~~oriented~~trending planar structures (Edfelt et al., 2006). At the Ekströmsberg IOA deposit, Frietsch (1974) reported several ~~prominently developed~~prominent structures, including NW-trending schistosity ~~that~~ parallel to the orientation of the main ~~ore bodies~~orebodies. Additional structural components ~~including~~include locally developed ~~folding~~folds, a major NW-~~SE~~trending and smaller NE-trending fault ~~zone~~zones, and ~~tectonically crushed feldspar~~brecciated phenocrysts ~~were also noted~~ (Frietsch, 1974). Overall, these features imply a polyphase structural evolution for the Ekströmsberg IOA deposit ~~but further~~based on plastic fabrics intersected by brittle deformation zones. Further detailed descriptions of ~~its~~the structural characteristics of the Ekströmsberg IOA deposit are presently lacking, however.

~~4 Methodology and study approach~~

4 Methods

In this study, five key areas were chosen to ~~elucidate~~study the structural differences and/or similarities along the WSB; from Eustiljåkk, Ekströmsberg, Tjårrojåkka, Kaitum West and Fjällåsen-Allavaara (Fig. 2, 3). Geological mapping with a structural focus was conducted between 2015 and 2017. A total of 698 outcrop observations were made and 1079 structural measurements were collected. The mapping campaign covered all ~~major outcrop~~ outcropping areas between Allavaara in the south to Eustiljåkk in the north (Fig. ~~1, 2).~~1, 2), although it should be noted that the total outcrop exposure for the WSB is estimated at c. 1 - 3 % by surface area. All structural measurements were collected using Brunton Geo Pocket Transits and ~~all~~the data were digitized in the field on ruggedized iPad mini devices using the ~~Middland Valley~~ application Field Move (former Midland Valley Exploration Ltd~~.). All lineations~~., currently Petroleum Experts Ltd.). Lineations were measured as the pitch on planes and recalculated into true orientation using the software Geo Calculator (Holcombe, Coughlin, Oliver, Valenta Global). For magnetite-rich rocks, structural measurements were estimated using known distal points in the terrain. Structural analysis was performed using ~~the~~ Move 2017 software package (former Midland Valley Exploration Ltd~~.) and Leapfrog Geo 4.0 (Seequent),~~., currently Petroleum Experts Ltd.), whereas maps were constructed using ArcMap (ESRI). Stereographic plots were produced as lower-hemisphere, equal-area stereographic projections using Dips 7.0 (Rocscience). Forty-one oriented samples were collected throughout the study area. The samples were cut across foliation and parallel to lineation and sent to Vancouver Petrographics Ltd. for thin section preparation, one thin section per sample. Petrography and microstructural investigations were performed using a conventional petrographic polarization microscope equipped with a digital camera (Nikon ECLIPSE E600 POL).

The characterization of hydrothermalHydrothermal alteration mapping was approached from a "conducted via field geology" or exploration perspective.observations at the outcrop- to hand sample-scale using 10x hand lenses. We focused on the recognition of mappable alteration mineral assemblages at the outcrop- to hand specimen-scaleassociations to establish possible links between certain structures and alteration styles, and identify specific structural- and/or alteration combinationscharacteristics that may prove useful as a vectoring tool toward Fe and/or Cu mineralization. The purpose of this approach was to provide a holistic overview of paired deformation-hydrothermal processes affecting the WSB, and this scientific contribution offers a starting point for further studies on the evolution of hydrothermal mineral alteration-related studies in this underexplored area.

5 Results

In general, the structural mapping results highlight severaltwo superimposed ductile and brittle-ductile deformation events that generated plastic and brittle-plastic structures along the WSB that vary in terms of their character and intensity. Likewise, variably developed hydrothermal alteration displays localized differences in terms of type, style and intensity. In Sections 5.1 – 5.5, the main structural features from the five key areas are presented from north to south, with a description of the alteration characteristics for the WSB outlined in Section 5.6.

5.1 Eustiljåkk area

The Eustiljåkk area provides a relatively continuouslywell exposed, c. E-W profile cross the northern WSB (Fig. 42, 5). The area predominantly comprises weakly deformed porphyriticporphyric volcanic rocks, along with subordinate metasedimentarysedimentary rocks and mafic dykes. WestSteep west-dipping shear zone-type structures occur in the NE-part of the area and impart a dominant N-S-directedtrending structural grain in this sector (Fig. 45). Beyond this area to the west, other large-scale cac. NW-alignedtrending structures are interpreted from magnetic anomaly data (Bergman et al. 2001, Fig. 3). Although ground truthing of these more western structures was not possible due to poor exposure, their continuity was verified by structural measurements and thin section analysis of similarly deformed rocks along strike in key areas south of Eustiljåkk (Sections 5.2, 5.4 and 5.5 below)..

In general, a weakly developed penetrative cleavage is present throughout the Eustiljåkk area. We designate this cleavage as S_1 because it is folded into mesoscale F_2 folds with near vertical-plunging F_2 foldsfold axes (Fig. 4: further descriptions below).5). NNW-SSE or N-S-trending and west-dipping structural grains that are parallel with magnetic lineaments appear to control the orientation of S_1. cleavages (Fig. 5, 6). The magnetic lineaments predominately have NNW-SSE orientations (Fig. 3) whereas the stereographic projection of S_1-foliations from the entire Eustiljåkk areamap indicates a dominantly N-S grain that NNW-SSE trending planar structures are the more dominant trend compared to N-S-oriented structures at Eustiljåkk (Fig. 5).3, 5), whereas stereographic projections of S_1- foliations indicate a N-S structural grain as dominant (Fig. 6). This probably results from a bias in the S_1 summary plot (Fig. 5a-b) due to contradiction likely reflects a greater surface exposure of N-S directed magnetic lineaments in the area which lead to a higher in out cropping areas containing c. N-S-oriented planar structures, giving a greater number of structural measurements along this grain.with N-S orientations as shown in the S_1 summary stereographic plot of the Eustiljåkk area (Fig. 6a-b).

S_1 foliation is defined by a preferred mineral orientation of feldspar + quartz ± biotite ± actinolite ± hornblende in felsic to intermediate to felsic volcanic rocks (Fig. 6a7a) and adjacent granitoids. The cleavage distribution in the granitoids is unevenly distributed and is generally of low intensity. South ofIn the area between Eustiljåkk area,and Ekströmsberg (Fig. 2), calcite is alsoforms part of the cleavagefoliated mineral assemblageassociation within porphyriticporphyric volcanic rocks. In mafic rocks, S_1 is defined by actinolite + plagioclase ± epidote ± hornblende ± calcite that show a preferred mineral orientation parallel to the ca N-S-aligned S_1 fabric.

In general, bedding surfaces (S_0) are only rarely preserved in the Eustiljåkk area. In the southern part (Fig 45), deformed meta-arkosicarkose horizons are interbedded with more competent volcanic porphyriesporphyric rocks. The more western of these horizons is slightly steeper and shows intense NNE-verging parasitic F_1 foldingfolds with M- and Z-geometriesgeometry (Fig. 6b7b). Based on bedding-bedding and bedding-cleavage relationships, combined with parasitic fold geometries, we interpret the foldlarger scale structure as a NE-verging, overturned synform. An axial planar parallel S_1 cleavage generally dipslocally associated with the F_1 folds strikes sub-parallel to bedding but is slightly steeper than bedding (dipping (see inset stereoplots in Fig. 45). The calculated F_1 beta axis (β: 330/15) plunges gently towards the northwest, which is comparable to the measured NW-plunging fold axes of parasitic F_1 Z-folds (Fig. 5). $F_1$4). The fold limbs are transected by an E-W aligned trending high-strain zone in the southern Eustiljåkk area as inferred from the aeromagnetic map and supported by high-strain cleavage measurements near the magnetic lineament (Fig. 4). The axial5). Axial planar S_1 cleavage appearsappear to be locally transposed into thethis high-strain zone (Fig. 45). We interpret this phenomenon as localized folding (transposition) of S_1 and S_0 in response to D_2 shearing. In the northwestern part of the Eustiljåkk map sheet, a low-intensity S_1 cleavage is folded into inferred F_2 folds. Stereographic analysis indicates slightly asymmetrical fold geometries with a calculated beta axis (β:293/79) plunging steeply (β:293/79) towards the northwest (Fig. 4). In terms of overprinting structures, D_2-related5). Corresponding F_2 fold hinges (F_2) and axial planar parallel cleavages (S_2) were not observed in the field nor in thin sections.

The northeastern part of the Eustiljåkk area (Fig. 45) is characterized by mainly N-S and subordinate NW-SE and NE-SW-trending sets of thin, well-exposed high-strain zones. Associated stretchingStretching lineations show variable orientations (Fig. 45). In relatively low strain units, S_1 cleavages plot near the best fit plane (Fig. 4)5), suggesting F_2 folding around a calculated beta axis plunging steeply to the north (β:357/79), whereas the high-strain D_2 fabrics (designated S_2) are oriented consistently N-S (Fig. 45). Mafic dykes are commonly encountered either within or at the contacts of the high-strain zones

(Fig. ~~6c). The~~7c) and are interpreted to reflect magmatism during D_2 deformation. Locally, mafic dykes ~~sometimes~~ show internal folding of leucocratic material (possibly albititized dolerite) but relatively undeformed dykes ~~are~~ also ~~present~~occur. The mafic dykes are in most cases not wider than a couple of ~~meters~~metres and occur as swarms. ~~Where dyke density is high, the dykes were mapped as single units.~~ The high-strain zones and related mafic dykes ~~affect a surrounding~~transect the granitoid pluton bordering the volcanic rocks in the east, implying granitoid emplacement occurred prior to D_2-related deformation and mafic magmatism.

Oriented thin ~~section samples from the Eustiljåkk area~~sections did not yield any high confidence kinematic indicators making the kinematic interpretation of ~~the area difficult.~~Eustiljåkk uncertain. Despite this, ~~an~~the east-verging F_1 fold in the southern part of the area (Fig. ~~4) indicates that~~5) suggests the Eustiljåkk area was affected by west-side-up movements during D_1.

5.2 Ekströmsberg area

The Ekströmsberg key area (Fig. ~~7~~8) is dominated by felsic to intermediate ~~metavolcanic~~volcanic rocks that host the Ekströmsberg IOA deposit (Frietsch, 1974). ~~The dominating~~Dominant NNW-SSE trending high-strain deformation zones west of the Ekströmsberg IOA deposit (Fig. ~~8) is~~9) are poorly exposed and ~~is~~are mainly inferred from aeromagnetic and ground magnetic anomalies (Frietsch et al. 1974, Bergman et al., 2001). These magnetic anomalies can be linked to high-strain zones mapped just northwest of the Ekströmsberg IOA deposit (Fig. ~~8~~9) and further south in the Kaitum West area (Fig. ~~11~~12, Section 5.4).

~~At Ekströmsberg, a~~A penetrative, continuous cleavage is defined by a preferred ~~mineral~~ orientation of feldspar + quartz ~~and/or~~± biotite ~~or~~± amphibole (mean orientation: 251/50). ~~The~~We designate this fabric S_1 because its orientation ~~of this cleavage appears to be~~is partly controlled by ~~adjacent high-strain zones, hence suggesting this cleavage as S_1 generation. This fabric is~~ later D_2-structures (see below). S_1 fabrics are developed in both ~~the~~ supracrustal and plutonic rocks ~~in the Ekströmsberg area~~, although~~,~~ ductile ~~deformation~~fabrics only sporadically ~~occurs~~occur in the ~~plutonic rocks.~~latter. A mineral stretching lineation is generally present in felsic-intermediate volcanoclastic rocks and is defined by stretched feldspar ~~porphyroclasts~~ and quartz. Occasionally, a ~~very~~ well~~-~~developed mineral lineation (L_m) in mafic rocks is defined by ~~strained~~ actinolite-tremolite forming a distinct L-~~tectonites~~tectonite (Fig. ~~8a). Nevertheless, the~~ 9a). In general ~~trend in the area is the development of~~, however, LS-tectonites~~.~~

~~Metasedimentary rocks are rare at Ekströmsberg and few clear bedding planes could be observed. Sedimentary rocks~~ are ~~only present~~more commonly developed at Ekströmsberg.

Subordinate sedimentary rocks occur in the northwestern part of the ~~area, comprising~~Ekströmsberg area and mainly comprise poorly sorted, polymict conglomerate ~~horizons~~ with poorly developed or indistinct bedding features (Fig. ~~7).~~8), at a stratigraphic position corresponding to the Kurravaara conglomerate (Fig. 4). Locally, pillow ~~basalts provide~~basalt provides reliable bedding markers ~~and~~, especially where primary magmatic layering is indicated by stratiform scapolite replacement (Fig. ~~8b). Due to the general lack of high confidence bedding markers few well exposed fold shapes has been observed.~~

~~Lithological~~9b). Additionally, lithological contacts (Offerberg, 1967~~) and~~), structural lineaments derived from magnetic maps (Frietsch et al., 1974, Bergman et al., 2001) ~~were used to indicate fold symmetries where lithological contacts and magnetic lineaments bend in association with small-scale fold axes could be observed~~ and measured ~~in field (Fig. 7). S_1 cleavages are typically developed~~ fold axes (designated F_1) were used to infer fold geometries at Ekströmsberg (Fig. 8). In general, S_1 foliations are axial planar~~-parallel~~ to ~~these inferred~~ F_1 folds~~.~~ with steep, south-plunging fold axes (Fig. 8). A low intensity foliation of ~~a somewhat~~ uncertain origin is commonly observed in ~~porphyritic~~felsic porphyric volcanic rocks (Fig. ~~8c~~9c, d). This ~~structure~~planar fabric is defined by a preferred orientation of feldspar and quartz which locally resembles a tectonic cleavage~~. Nevertheless, no or very little signs of~~, although pressure shadows and/or re-crystallization around ~~the feldspars could be~~feldspar phenocrysts were not observed (Fig ~~11~~8d). We ~~suggest~~interpret this fabric as a ~~flow fabric implying that a~~ primary (S_0) magmatic ~~foliation (S_0)~~ flow fabric which may ~~be discernible in the Ekströmsberg area and that this foliation correlates~~correlate to what Frietsch (1974) described as "fluidal banded" ~~(Cc.~~volcanic rocks at Ekströmsberg (See Fig. ~~8~~9 in Frietsch, 1974). ~~This interpretation is supported by~~ In the southern Ekströmsberg area, the magmatic fabric evident in felsic volcanic rocks is folded into a tight, upright and near-cylindrical, F_1 fold with a steeply plunging fold axis (β: 195/75~~), near cylindrical, tight and upright folding of this S_0 fabric whereas the clearly tectonic, continuous, low intensity S_1 cleavage does not show this folding pattern (Fig. 8).~~

~~The~~). A NNE-oriented, sub-vertical foliation is parallel to the fold's axial plane and is interpreted as an axial planar cleavage designated S_1 ~~cleavage appears~~.

Inferred S_1 cleavages in felsic volcanic-volcanoclastic rocks appear to be transposed into a set of sub-vertical, E-W-trending strike-slip- and NNW-SSE-trending reverse dip-slip shear zones near the Ekströmsberg IOA deposit~~.~~ (Fig. 8). We interpret this effect as the transposition of S_1 cleavage into ~~D_2~~later formed shear zones ~~implying that, as in the Eustiljåkk area,~~(S_2) and thus marking two compressional deformation events ~~can be recognized~~ (i.e. D_1 and D_2). A mafic volcanic rock in the northwestern part of the key area shows a crenulation cleavage ~~developed in~~within a NNW-SSE-trending reverse dip-slip ~~mylonitic~~mylonite zone, which also ~~suggesting~~suggests two fabric-forming events (Fig. ~~8e).~~ 9e).

~~The~~Shear sense ~~of shear~~ determined from SCC´-fabrics in thin ~~section~~sections of foliated volcanic rocks indicates oblique west- to southwest-side-up kinematics ~~in~~for the ~~dominating~~main NNW-SSE-trending high-strain zones~~.~~ at Ekströmsberg. Oblique sinistral (~~8f~~Fig. 9f) and reverse dip-slip (~~8g~~Fig. 9g) movements are recorded along ~~north- and near-vertical~~moderately N- to NNW-plunging and subvertical stretching lineations respectively, with both ~~yielding~~suggesting overall west-block-up kinematics. ~~The~~Approximately E-W-trending ~~mylonites within~~ mylonite zones in felsic volcanic rocks close to the Ekströmsberg IOA deposit (Fig. ~~7~~8) show strike-slip ~~movements~~movement with a sinistral top-to-the-west sense-of-shear as indicated by ~~S-C fabric orientations (Fig. 8h). Interestingly, many of the feldspar porphyroclasts in the E-W high-strain zones at the Ekströmsberg IOA deposit record brittle deformation (Fig. 8i). No brittle deformation of feldspars was observed in the NNW-SSE-trending mylonites throughout the entire WSB.~~SC-fabrics (Fig. 9h). No direct ~~cross-cutting~~crosscutting relationships between the E-W- and NNW-SSE-trending high-strain zones ~~could be~~were observed ~~in~~at the ~~field~~outcrop scale. However, ~~an~~ E-W tectonic ~~grain offsets the~~fabrics tends to offset NNW-SSE~~-grain~~-oriented lineaments on magnetic maps

(Bergman et al., 2001; Frietsch et al., 1974) throughoutalong the WSB, (Fig. 3), suggesting the latea later timing of thesefor E-W high-strain zones on a regional- to belt--scale. Both structural grains show

Close to the Ekströmsberg IOA deposit, feldspar porphyroclasts in felsic volcanoclastic rocks and transected by E-W high-strain deformation zones record the effects of brittle deformation (Fig. 9i). In contrast, this type of grain-scale brittle deformation was not observed in similar feldspar-phyric lithologies deformed by NNW-SSE-trending mylonite zones along the WSB. Rocks affected by both structural trends also show sub-grain rotation (SGR) and quartz recrystallization textures with local bulging (BLG) recrystallization (Cf. Fig. 8e, c.f, g. Fig. 9f, h) indicating relatively low , i). Overall, this textural evidence suggest recrystallization proceeded at approximately 400° C (Passchier & Trouw 2005), although a slightly lower temperature conditions ((< 400°C) is indicated by the brittle character of feldspar within the E-W-trending shear zones (Fig. 9i; c.f. Passchier & Trouw 2005).

5.3 Tjårrojåkka area

The Tjårrojåkka area (Fig. 9) is dominated by10) mainly comprises felsic and intermediate volcaniclastic, volcanoclastic and volcanic and volcanosedimentary rocks that host the Tjårrojåkka Fe-Cu system (c.f. Edfelt et al., 2005). The Primary bedding (S_0) is locally visible in laminated volcanosedimentary rocks and greywacke. Throughout the area is dominated by, a visibly dominant, penetrative S_1 planar foliation occurs and is generally oriented subparallel to S_0 bedding/laminae. This planar structure, here designated S_1, is defined by the mineral alignment of amphibole, quartz, feldspar and locally magnetite. Bedding (S_0) is locally visible in laminated volcanosedimentary rocks and greywackes. S_0 is generally sub-parallel to S_1 and shows local, in the volcanic-volcanoclastic rocks and is axial planar to meso-scale, intrafolial isoclinal folds (Fig. 10a). At the macro-scale, S_0 appears to form an11a). In the central part of the key area, S_0 bedforms are folded by a major ENE-WSW-aligned, isoclinal F_1-fold with an approx. ENE-WSW-trending main structural grainsequence which, based on its surface trace, shows apparent re-folding (Fig. 910). Mineral lineations are generally observable as an alignment of amphibole and quartz on S_1-foliation planes. Both bedding and S_1 foliations are overprinted by F_2-folds with axial traces trending approx. N-S to NE-SW (Fig. 910). F_2- fold geometries are upright, open to closeclosed, and show a distinct,distinctive spaced cleavage that is parallel to their axial surface parallel spaced cleavage,traces and is here designated S_2. The N- to NE-aligned S_2- cleavage is commonly defined by biotite alignment in felsic volcanic rocks and also by brittle fracturingfractures. Spacing of the S_2- cleavage ranges from a few cm up to several tens of cm (Fig. 10b11b, c). Locally, S_2-related kink bands are relatively common features in volcaniclasticvolcanoclastic rocks (Fig. 10 b11b). In general, the dominate NE-trend of S_1 mimics the orientation of a NE-SW-striking high-strain zone hosting the Tjårrojokka copper-goldTjårrojåkka Cu-Au deposit (c.f. Edfelt et al., 2005, 2006).

5.4 Kaitum West area

The Western Supracrustal Belt progressively widens southward toward the Kaitum West area (Fig. 2, 1112). Overall, the bedrock in this area is dominated by felsic to intermediate metavolcanicvolcanic to volcanoclastic rocks with some additional relatively common metabasaltbasalt sequences. Kaitum West provides an almost continuous mappable E-W profile across the

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~~WSB.~~ Structural observations indicate the area constitutes several low-strain zones that border a central high-strain block (Fig. ~~11). The main~~ 12). Most of the strain ~~was taken up~~is apparently accommodated by relatively narrow shear zones ~~concentrated in~~ transecting felsic volcanoclastic rocks~~. The surrounding metabasaltic~~ in the central part of the area (Fig. 12). Locally to ~~meta~~ the west, highly strained basaltic and andesitic ~~volcanic~~ rocks do occur, however, these sequences generally show ~~lower~~low strain ~~intensities and the~~ intensity.

Bedding markers are rare in the Kaitum West area and F1 folds was not recognized. Within the high-strain central block (Fig. 12), a polymict and poorly sorted clastic horizon occurs (Fig. 13a, b). This horizon contains a penetrative S_1 cleavage (266/79) defined by sericite + biotite + chlorite dominated shear bands that trend sub-parallel to bedding and is particularly well developed at the margins of compositional layers (Fig. 13a). At the outcrop-scale, the S_0/S_1 composite fabric is isoclinally folded (Fig. 13b) around a measured fold axis (335/60) plunging moderately to the NW. Locally, a S_1 high-strain cleavage is transposed into later shear bands (possibly S_2) that parallel the main shear zone system (Fig. 13 c, d). This indicates relatively high ductile strain was localized both during D_1 and D_2 in the Kaitum West area.

The easternmost low-strain block ~~shows~~is affected by F_2 folding around a calculated beta ~~axes~~axis plunging steeply to moderately towards south (β: 182/67: Fig. ~~11~~12). Within the central high-strain block, several NW-SE-, N-S-, and locally E-W-trending high-strain zones and shear zones are present (Fig. 12). We interpret the central high-strain block as the northern continuation of the shear zone system mapped in the Fjällåsen-Allavaara area (see section 5.5).~~ Within the high-strain block, several NW-SE-, N-S-, and locally E-W-trending high-strain zones and shear zones are present (Fig. 11). The shear zones are best developed in volcanoclastic rocks, although highly strained intermediate and mafic volcanic rocks also occur.~~

~~Bedding markers are rare in the Kaitum West area, however, local volcanosedimentary horizons show bedding markers. Within the high-strain block, a polymict and poorly sorted clastic horizon occurs (Fig. 12a, b). This horizon shows an S_1 cleavage (266/79) developed as sericite, biotite, chlorite dominated shear bands sub-parallel to bedding and is particularly well developed at the margins of compositional layers (Fig. 12a). At outcrop-scale, the S_0/S_1 composite fabric is isoclinally folded (Fig. 12b) around a measured fold axis (335/60) plunging moderately towards NW. Locally, a S_1 high-strain cleavage is transposed into shear bands that parallel the main shear zone directions (Fig. 12 c, d). This indicates relatively high-strain was localized both during D_1 and D_2 in the Kaitum West area.~~

Kinematic indicators in the Kaitum West area suggest southwest-side-up and shallow to steep oblique dextral ~~displacements~~displacement that ~~are~~is associated with ~~southward~~a south-plunging stretching ~~lineations~~lineation. This interpretation is based on SCC´ fabrics and a asymmetric quartz ~~sigmoids~~sigmoid with stair stepped pressure shadows (Fig. ~~12e~~13e). The same sense-of-shear is indicated by a sinistral SC~~ fabrics~~ fabric (Fig. ~~12f)~~13f) observed along a north plunging stretching ~~lineations~~lineation north of the Kaitum West area (south of Ekströmsberg; Fig. 2, 3) where the same shear zone system is related to a major fold structure~~.~~ (Fig. 12). Locally, a contradicting sense-of-shear (east-block-up) is indicated by asymmetric sigma clasts with poorly developed pressure shadows.

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5.5 Fjällåsen-Allavaara area

The area between Fjällåsen and Allavaara is dominated by felsic, intermediate and mafic volcanic~~, volcaniclastic~~ and ~~volcanosedimentary~~volcanoclastic rocks. The~~ overall~~ dominant structural grain is an approx. N-S-trending set of high-strain zones (Fig. ~~13~~14) associated with a well-developed N-S-trending penetrative foliation. The foliation is defined by the alignment of strained amphibole, biotite, feldspar, quartz and locally magnetite (Fig. ~~14a~~15a) and is here assigned S_1. Bedding is locally observable as compositional layering in volcanosedimentary rocks and is typically sub-parallel to the S_1-foliation. Locally, isoclinally F_1~~-~~-folded quartz and amphibole veins and bedding can be observed (Fig. ~~14b~~15b, c). Shearing is ~~commonly observed~~common and localized in prominent high-strain zones ~~transposing~~that transpose S_0 and S_1 and ~~forming~~form distinct mylonites (Fig. 15d). S_0 and S_1 are folded openly to tightly into meso-and macro-scale F_2 folds (Fig. ~~14d).~~15e, f). An axial surface parallel cleavage (S_2) is locally observable as a weakly developed, brittle, spaced cleavage (Fig. 15e, f). Locally, this S_2 cleavage shows en-echelon fracturing (Fig. 15b). Mineral lineations variably plunge steeply to moderately towards the north and south. Based on asymmetric sigma clasts and SC-fabrics a reverse, west-block up sense-of-shear is interpreted for the majority of deformation zones in this area. The central shear zone in Fjällåsen hosts the Fjällåsen Cu-prospect and shows oblique kinematics with a reverse west-block up and sinistral sense-of-shear along a mineral lineation plunging 60° N (Fig. ~~13~~14). ~~). S_0 and S_1 are folded openly to tightly into meso-and macro-scale F_2 folds (Fig. 14e, f). An axial surface parallel cleavage (S_2) is locally observable as a weakly developed, semi-brittle, spaced cleavage (Fig. 14e, f). Locally, the S_2 cleavage shows en-echelon fracturing indicating a certain amount of brittle movement (Fig. 14b). Mineral lineations are variably plunging steeply to moderately towards the north and south.~~

5.6 Metamorphism and hydrothermal alteration along the WSB

~~In this section, descriptions of~~Mineral alteration ~~mineral assemblages follow the qualitative approach of Gifkins et al. (2005) and are summarised in Figure 16. Alteration assemblages that were temporally resolvable~~ associations identified along the WSB based on mineralogical, textural, cross-cutting and/or overprinting relationships are ~~classed as a separate assemblage. We recognise that these assemblages~~presented in this section. Although several associations likely ~~form part of~~ formed in response to a progressively evolving ~~metasomatic~~ and likely protracted hydrothermal system~~ but this approach was favoured to~~ (s), the new alteration mapping results provide a field-based classification/paragenetic scheme for the various alteration occurrences.

An epidote + plagioclase + hornblende association occurs parallel to S_1 fabrics in mafic volcanic rocks in the Ekströmsberg area and forms a moderately intense and pervasive metamorphic mineral association (Fig. 16a). Additionally, veins hosting hornblende + epidote locally occur and preserve internal foliations that are laterally consistent with S_1 fabrics in adjacent wall rocks (Fig. 16a), suggesting a relatively early timing (i.e. pre- to syn-D_1). However, hornblende shows syn-tectonic growth (Fig. 16b, c) and the S_1 foliation can be continuously traced within the matrix and as a preserved S_1 in the hornblende indicating that the vein mineralogy was altered during prograde metamorphism approximately broadly coincident with D_1. In the

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Eustiljåkk area (Fig. 2, 5), epidote commonly developed as a retrograde product replacing disseminated hornblende porphyroblasts, indicating retrograde metamorphic processes affected the area.

Scapolite ± albite hydrothermal alteration overprints pervasive magnetite + amphibole alteration of basaltic rocks in the Kaitum West area. However, scapolite ± albite alteration is also locally overprinted by irregular and patchy amphibole + magnetite zones that tend to be developed along S_1 foliations (Fig. 17a). Thus, both associations are interpreted to be broadly coeval and formed during D_1. Discordant magnetite + amphibole veins with white to buff albite haloes occurs locally in basaltic rocks with low strain intensities (Fig. 17b) and affected by more pervasive (disseminated) magnetite + amphibole alteration.

In general, scapolite ± albite alteration is ~~relatively~~ common throughout the WSB and is mainly ~~observable~~observed in compositionally mafic rocks (i.e. ~~metabasalt, metadolerite~~basalt and dolerite) as a distinctive, speckled (porphyroblastic), pale grey to creamy white ~~texture~~granular discolouration on exposed surfaces (Fig. ~~15a~~17c). Disseminated scapolite porhyroblasts are typically medium- to coarse-grained (1 – 8 mm), irregular tabular to elongate prismatic, and ~~occupy ca~~represent c. 10 – 35 vol. % of altered rock units (Fig. ~~15a, c). The weakly~~17c). Weakly to strongly developed porphyroblastic scapolite ± albite alteration is ~~regionally distributed and~~ best preserved in relatively low strain areas adjacent to or within NNW- to N-trending ~~D_1-related~~ shear zones. In the Eustiljåkk area (Fig. 2, 3), porphyroblastic scapolite alteration affects mafic dykes in zones with relatively high strain ~~(D_1 and D_2),~~, while it locally overprints inferred S_0 bedding planes in basalt units in the Ekströmsberg area (Fig. 2, 3, 8b). ~~Discordant, vein-related scapolite ± albite alteration also locally occurs and is paragenetically late relative to patchy porphyroblastic~~Discordant, vein-hosted scapolite ± albite~~, although these~~ alteration is widespread in the Vieto area (Fig. 2, 3). These veins are affected by shearing with a probable D_2 timing (Fig. ~~15b). Scapolite ± albite alteration overprints pervasive magnetite + amphibole alteration but is also locally overprinted by irregular and patchy amphibole ± magnetite zones that tend to be developed along S_1 foliations (Fig. 15c). Thus, both assemblages are interpreted to have formed synchronously during D_1. Discordant magnetite + amphibole veins with white to buff albite haloes also occur (Fig. 15d) and appear to have formed synchronously with the more pervasive (disseminated) magnetite + amphibole alteration~~17d), hence, the veins are interpreted as being formed pre-D_2.

~~Relatively intense and pervasive~~ Deformed and discordant calcite veins are common throughout the WSB and are mainly present in low-strain blocks dominated by mafic rocks. However, pronounced calcite alteration also shows syn- to post-D_2 timing since it overprints clear S_2 shear zone fabrics in high strain zones. Syn-tectonic (D_2) calcite associated to sparse occurrences of sulfide (pyrite + chalcopyrite) overprints relatively intense and pervasive tremolite-actinolite alteration ~~occurs~~(Fig. 17e) at one locality in the northern part of the Ekströmsberg area where it forms part of an ~~amphibolite~~amphibolitic L-tectonite within a steep, reverse~~,~~ dip-slip shear zone ~~(Fig. 8a). This assemblage is overprinted by syn-tectonic (D_2), relatively intense and pervasive calcite alteration and post-tectonic, undeformed, granular epidote (Fig. 15e). Syntectonic calcite alteration is also present several km north of this locality along the same structure.~~that transects mafic rocks (Fig. 9a). Intense and pervasive calcite alteration ~~(Fig. 15f) also occurs~~shows a post-D_2 timing in the nearby Vieto area (Fig. 2, 3) where ~~it is related to~~relatively undeformed calcite overprints an S_2 fabric in a moderately (c. 285/75) west-dipping shear zone~~. Here,~~

calcite alteration overprints ductile shear zone fabrics and the timing of calcite is therefore interpreted as late- to post-D_2 deformation at this locality. Deformed and discordant calcite veins, with a probable D_1 timing, are also common throughout the WSB and are mainly present in low-strain blocks dominated by mafic rocks.

Epidote forms part of several alteration assemblages with differing parageneses and structural associations along the WSB. For example, epidote together with hornblende and plagioclase occurs parallel to S_1 fabrics (likely syn-D1) inintersecting Rhyacian metabasalts to form a probably regionally distributed, moderately intense and pervasive metamorphic key assemblage (Fig. 15g). Additionally, early developed (pre- to syn-D_1) hornblende + epidote veins locally occur and are affected by S_1 foliations (Fig. 15g). In the Eustiljåkk area, epidote is also commonly developed as a retrograde product replacing disseminated hornblende in mafic metavolcanic rocks. A relatively intense, selectively pervasive epidote + K-feldspar assemblage, spatially related to localized Cu-sulphide weathering overprints a weak, pervasive amphibole + magnetite alteration in the western low-strain block of the Kaitum West area (Fig. 15hbasalt (Fig. 17f).

The most prominent alteration assemblageHydrothermal mineral associations restricted to D_2 structures are in general potassic-ferroan in character comprising K-feldspar, quartz, and epidote associated to Fe-oxide and sulfide. The most prominent alteration association in the Tjårrojåkka area is a relatively intense and pervasive K-feldspar + epidote + quartz hydrothermal alteration assemblageassociation that overprints and cuts S_1 foliationsfoliation. Locally, both K-feldspar and epidote appear to be remobilized into S_2 spaced cleavage domains. Epidote also commonly occurs as patches on fracture planes at Tjårrojåkka, producingwell as volcanosedimentary bedding (Fig. 17g). In the Kaitum West area, a distinctive reddish-green rock (Fig. 15i). Epidote also occurs in areas of often moderate to relatively intense, selectively pervasive epidote + K-feldspar alteration (replacing albite) throughout the WSB (Fig. 15j) andassociation is typically accompanied by spatially related to localized Cu-sulfide weathering and overprints a weak retrograde sericite alteration of secondary K-feldspar. Overall, this assemblage commonly affects intermediate to felsic metavolcanic rocks that may also display the effects of earlier formed scapolite and/or, pervasive amphibole ±+ magnetite alteration where K-feldspar ± epidote is less intensely developed. These overprinting relationships and the more localized (selectively pervasive) distribution of the K-feldspar + epidote assemblage suggests it formed during a later alteration event (i.e. post-D_1).

in a mafic volcanic rock (Fig. 17h). In the Ekströmsberg area, a relatively intense, shear band-hosted biotite + magnetite + K-feldspar + muscovite assemblage affectingassociation affects a rhyodacitic volcanosedimentary rock is associated with intersected by steep, approximately E-W-strikingtrending sinistral strike-slip shear zones with a D_2 timing (Fig. 15k17k, l). The biotite-bearing shear bands are oriented subparallel with the volcanosedimentary bedding (S_0). Magnetite also occurs along the same shear bands and as disseminated grains in the adjacent wall rock. We interpret the timing of this alteration to be synchronous with the last activity of the structure, hence D_2 (see section 5.2).

Selectively pervasive K-feldspar alteration (replacing albite) is common in intermediate to felsic volcanic rocks throughout the WSB (Fig. 17k) and is typically accompanied by weak retrograde sericite and hematite staining of secondary K-feldspar as well as epidote. K-feldspar alteration of albite of this type is the only hydrothermal alteration with a syn- to- post D_2-timing that is pervasive over large distances and not directly associated to tectonic structures.

The paragenetically latest hydrothermal mineral alteration identified in this study constitutes epidote forming patches on fracture planes intersecting selectively pervasive K-feldspar alteration at Tjårrojåkka. This association produces a distinctive reddish-green rock (Fig. 17l) with a late timing relative to brittle deformation (veins and fractures) of uncertain timing.

The hydrothermal mineral alteration associations identified in this study are summarized as a simplified alteration map in Figure 18. The map shows that magnetite + amphibole alteration is spatially correlated to scapolite ± albite alteration, with the latter affecting large areas at some distance from dominant structures. The intensity of the potassic alteration seems to decrease towards the north and increases towards south where c. 1.8 Ga granites are found. The uncertainty of the map is relatively high due to the generally low rock exposure of the WSB.

Overall, the identified metamorphic and hydrothermal mineral associations are summarized as follows:

D_1-related fluid flow (or marginally later):

- Regional epidote-amphibolite facies metamorphism, early- to syn-D_1.
- Regionally pervasive amphibole + magnetite alteration, early- to syn-D_1.
- Discordant, vein-related amphibole + magnetite + albite alteration, early- to syn-D_1.
- Selectively pervasive scapolite ± albite alteration or growth of albite-scapolite porphyroblasts along S_0 and S_1 structures, syn- to late-D_1.
- Shear zone-hosted (selectively pervasive) actinolite + tremolite alteration, late-D_1.
- Calcite in veins with an uncertain temporal relationship to D_1, but probably pre-D_2.
- Scapolite in veins with an uncertain temporal relationship to D_1, but probably pre-D_2.

D_2-related fluid flow (or marginally later):

- Local S_2 shear band-filling biotite + magnetite + K-feldspar + muscovite alteration, syn-D_2.
- Local vein-related K-feldspar + epidote + iron oxide ± sulfide alteration, syn-D_2.
- Regionally distributed, patchy (selectively pervasive) K-feldspar alteration of plagioclase, syn- to post-D_2.
- Shear zone hosted calcite alteration, syn- and- late/post-D_2.
- Local fracture-filling and patchy epidote alteration, post-D_2.
- Retrograde sericite alteration, post-D_2.

6 Discussion

6.1 Structural evolution of the WSB

In general, the structural elements preserved within the WSB are consistent with a complex, polyphase deformation history. ObservedLocally, S_1 cleavages are axial planar to foldedF_1 folds affecting S_0 bedding planes and magmatic flow structures associated with ~~metasedimentary and~~sedimentary, volcanosedimentary, or volcanic rocks. Overall, F_1 folds are generally poorly exposed and are thus difficult to constrain due to the lack of clear bedding and/or stratigraphic ~~younging~~way-up indicators. Where ~~developed~~observed, however, F_1 folds are tight to isoclinal and are either upright or overturned, with the latter verging ~~to the east~~eastward (Fig. ~~4~~5, 7). ~~Interpreted~~ F_1 ~~folding~~folds in the southern Ekströmsberg area (Fig. 8) has ~~yielded~~ a relatively steep calculated beta axis that plunges towards the SSW (β: 195/75), which is a typical feature for ~~the~~ F_2 folds throughout the WSB~~. These similar orientations suggest earlier formed~~ and suggests some F_1 ~~folds~~fold axes were rotated into a steep southward plunge during D_2 transposition.

S_1 cleavages throughout the WSB are best preserved in relatively low-strain domains as a penetrative planar fabric in supracrustal rocks, while they are only weakly developed in ~~adjoining~~adjacent shoshonitic plutonic ~~bodies (equivalent to the~~rocks (i.e., Perthite monzonite suite ~~(PMS) of Bergman et al., 2001). In contrast, calc-alkaline plutonic rocks of similar age (Haparanda suite) typically display well-developed planar cleavages in northern Norrbotten indicating these~~ intrusions ~~formed pre- to syn-D1 (cf. Bergman et al., 2001). Based on the more intense foliations persevered in the calc-alkaline plutonic rocks compared to the shoshonitic intrusions, we~~; see Fig. 4). We interpret the relative timing of the ~~latter~~ shoshonitic (PMS) plutonic rocks as syn- to late-D_1. Reported ~~radiometric~~ igneous ages for ~~various intrusions assigned to this~~ shoshonitic (PMS) plutonic ~~suite in~~rocks across northern Norrbotten range from c. 1.88-1.86 Ga (Bergman et al., 2001, Sarlus et al., 2017, Kathol and Hellström, 2018). Thus, we interpret the absolute timing of syn- to late-D_1 deformation that affected the WSB to the later ages of the same time span, i.e. 1.88-1.86 Ga.

Mylonitization of volcanic-sedimentary rocks along the WSB frequently ~~occurs~~shows subparallel ~~with~~orientations to the regionally extensive and laterally continuous S_1 ~~cleavages~~cleavage. Although the level of ~~outcrop~~ exposure does not allow for accurate estimations of the width of these zones, our mapping ~~experiences~~experience combined with ground magnetic signatures in the Ekströmsberg area (Frietsch et al., 1974) ~~indicate~~indicates that these zones are relatively thin (meters to tens of meters~~) and display sharp contacts~~), controlled by lithological contrasts~~. The~~ (or primary depositional features), and display sharp contacts to adjacent lower strain rocks. Overall, the mylonitic strain ~~seems to have been taken up~~appears to be favourably partitioned by volcanoclastic and ~~metasedimentary~~sedimentary horizons that are sandwiched between more competent volcanic rocks throughout the WSB.

Penetrative fabrics formed during D_1 temporally coincide with the metamorphic peak indicated by syn-tectonic growth of hornblende in the Ekströmsberg area (Fig. 16b), implying temperatures at >450°C (e. g. Blatt et al. 2006). In comparison, similar temperature conditions are suggested by GBM-SGR dynamic quartz recrystallization textures observed in the Kaitum West area indicating temperatures at c. 500°C (Passchier and Trouw, 2005). However, dynamic quartz recrystallization textures (SGR with minor BLG) observed in D_1 shear zones suggest lower syn-deformation temperatures at c. 400°C (Fig. 9f). This may indicate that shear zone activity during D_1 post-dates the metamorphic peak and that non-coaxial strain dominated the deformation during the late stages of D_1.

In general, S_2 cleavages developed predominantly in NNW-SSE- and approx. E-W-trending high-strain zones. Where S_1 is not completely transposed into S_2 parallelism or overprinted by high-strain S_2 fabrics, the S_1 cleavage is ~~occasionally~~locally

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overprinted by a S_2 crenulation cleavage (c.f. Fig. ~~8e~~9e). Dynamic quartz recrystallization textures formed during D_2 in the mylonite zones (SGR texture with minor BLG) ~~suggest low to medium temperature conditions within these zones (Passchier and Trouw, 2005). In comparison, slightly higher temperature conditions are suggested for the Kaitum West area based on the presence of grain boundary migration (GBM) and SGR textures (Passchier and Trouw, 2005).~~suggests ambient temperatures of c. 400°C, however, brittle feldspar observed in association with SGR quartz textures (Fig. 9i) in an E-W-trending mylonite indicates the temperature as slightly lower (<400°C) in the E-W-trending structures during D_2 (Passchier and Trouw, 2005).

~~In the Tjårrojåkka area, Edfelt et al. (2006) identified three deformation events (D_1 – D_3 in Edfelt et al., 2006), although detailed structural information for each of these was not given. In their study, Edfelt et al. (2006) reported an early brittle-ductile deformation event (D_1), which generated steep NE-SW-directed planar structures that controlled the siting and orientation of the Tjårrojåkka Fe-Cu system. Subsequently, E-W oriented shearing and folding (D_2 structures) that was temporally associated with localized NNW-SSE-trending deformation (D_3 in Edfelt et al., 2006). Based on our mapping results (Section 5 and Figs. 7, 9, 11), we interpret ca E-W-directed high-strain fabrics at Tjårrojåkka (equivalent to D_2 structures in Edfelt et al., 2006) as relatively late structures (our D_2 event) since ca NNW-SSE-aligned fabrics are consistently affected (e.g. folded and displaced) by ca E-W-aligned structures throughout the WSB (Fig. 2, 3, 14a, 14d). In particular, the structural map of the Tjårrojåkka area shows isoclinal F_1 folds that are openly refolded by F_2 folds and offset by an E-W-directed D_2 high-strain zone (Fig. 9).~~

In low strain blocks throughout the WSB, S_1 planar structures are folded into meso-to macro-scale F_2 folds with fold axes generally plunging moderately to steeply (60-80°) northward or southward (Fig. ~~4, 9~~5, 10, 11, 12, 13). Axial planar~~-parallel~~ S_2-~~cleavages~~cleavage related to the F_2-folds in the low strain blocks are ~~very~~ rare. Only a few examples in the Tjårrojåkka, Fjällåsen, and north of the Ekströmsberg area have been observed ~~where S_2 forms an~~as axial planar~~-parallel~~, brittle~~-style~~, spaced ~~cleavage~~cleavages (Fig. ~~10b, 10c, 14d). Therefore, we suggest~~ 11b, 11c, 15e). This characteristic of D_2-deformation ~~occurred during relatively low-pressure, upper-crustal conditions (c. f. Pfiffner, 2017). In~~is typical for this part of Norrbotten and is also observed east of the WSB. For example, in the Gällivare area (Fig. 1), Bauer et al. (2018) ~~interpreted~~report folding of an S_1 gneissic fabric into F_2 synformal structures without axial planar S_2 ~~cleavages as low-pressure, shallow crustal level deformation.~~cleavage. In the Aitik Cu-Au-Ag deposit~~,~~, also near Gällivare (Fig. 1), Wanhainen et al. (2005) and Wanhainen et al. (2012) report lower amphibolite facies metamorphism and deformation at 500-600° and 4-5 kbar ~~at~~between c. 1.~~88~~89-1.87 Ga. This medium-grade tectonothermal event was later overprinted by a hydrothermal event estimated ~~to~~at 200-500°C and 1-2 kbar at c. 1.78 Ga based on fluid inclusion data and geochronology (Wanhainen et al., 2012). The findings in the Aitik Cu-Au-Ag and Malmberget IOA deposits may not be directly applicable to the WSB in terms of metamorphic-hydrothermal PT conditions but are ~~comparable~~compatible with ~~respect to~~ a ~~pronounced~~more intense earlier deformation event (regional D_1) overprinted by a weaker deformational event (regional D_2~~).~~), which we suggest represents the overall regional deformation history.

While the identification of two generations of planar fabrics is relatively straightforward in the WSB based on their ~~orientations~~orientation and interrelationships, linear structures are more difficult to interpret due to the lack of crosscutting

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relationships. ~~Stretching lineations measured on S_1 planes in low strain blocks are interpreted as L_1 structures. The orientation of L_1 lineations varies considerably more than stretching lineations measured in relatively high-strain zones (c. f. Fig. 17a-b).~~ Crenulation of mylonitic cleavage has only been observed along near vertical stretching lineation, which lead us to interpret the well clustered near-vertical stretching lineation ~~(Fig. 17b)~~in Figure 20 as L_2. The sense-of-shear associated with sub-vertical L_2-~~lineations~~lineation is reverse dip-slip (Fig. ~~8g~~9g) and is best explained by an E-W compressional stress field~~ (see also section 6.1.4). Shallow east-plunging lineations (Fig. 17b) were measured on relatively steep, approx. E-W-oriented planes offsetting the NNW-SSE grain, suggesting these structures as D_2-related structures. ~~. Sinistral strike-slip ~~movements along the shallow east-plunging lineation cluster (Fig. 17b)~~movement along steep, approx. E-W trending shear planes (Fig. 20b) offsetting the NNW-SSE-trending structural grain in the Ekströmsberg area ~~suggests these movement to have occurred as a response to E-W-directed crustal shortening ~~are D_2 structures and the associated shallowly east-plunging stretching lineation ~~cluster is~~is designated as L_2. Stretching lineations measured on S_1 planes in low strain blocks are interpreted ~~as L_2 (see section below~~to be L_1 structures. The orientation of L_1 lineation vary considerably more than stretching lineation measured in relatively high-strain zones (c. f. Fig. 20a-b). We suggest that the non-clustered shallow to moderately north and south plunging stretching ~~lineations~~lineation (Fig. ~~17b) within~~20b) of the NNW-SSE-trending mylonites might represent traces of ~~an early formed ~~L_1-lineation~~ within these high-strain zones.~~. The sense-of-shear ~~along these~~associated to the inferred L_1-~~lineations~~lineation is reverse oblique-slip SW-side up and best explained to result from NE-SW-directed crustal shortening. This implies that the kinematics of D_1 and D_2 are best explained by two compressional events that deviate approx. 45° from each other. Based on the assumption that traces of L_1 can be identified, we argue that the steep to near-vertical cluster in the low strain L_1-plot (Fig. ~~17a) might~~20a) represent L_1 ~~lineations~~lineation that were subsequently transposed during D_2 in a similar manner as F_1-fold axes were transposed in the Ekströmsberg area~~ (discussed in Section 5.2 above).~~.

The NNW-SSE-~~directed~~trending mylonites ~~containing~~with moderately plunging stretching ~~lineations~~lineation (L_1) suggest oblique-slip SW-side-up kinematics based on SCC´ fabrics and rotated porphyroclasts in oriented samples from the Ekströmsberg, Kaitum West, and Fjällåsen-Allavaara key areas. These kinematic indicators suggest both sinistral and dextral movements occurred, with dextral ~~movements recorded~~sense-of-shear observed along moderate S-plunging ~~lineations~~lineation (Fig. ~~12e~~13e) and sinistral ~~movements~~sense-of-shear observed along moderate N-plunging ~~lineations~~lineation (Fig. ~~8f, 14c~~9f, 15d). Similar kinematics are indicated during D_1 by the east~~-~~verging F_1~~-~~ fold in the Eustiljåkk area, implying consistent reverse oblique-slip southwest-side-up ~~movements~~movement during D_1 throughout the WSB.

The kinematics derived from ~~S-C~~SC fabrics along the near vertical lineations (L_2 generation) within the NNW-SSE-oriented mylonites in the Ekströmsberg and Fjällåsen areas indicate reverse dip-slip, W- to WSW-side up sense-of-shear (Fig. ~~8g~~9g). This implies a reactivation of the NNW-SSE-trending structures during an approx. E-W-directed D_2 shortening. Additionally, sinistral strike-slip ~~movements~~movement along E-W-trending shear zones in the Ekströmsberg area (Fig. ~~8h~~9h) indicate they were active during ~~ca~~a c. E-W compression ~~and ~~coincident with reverse dip-slip movements along the NNW-SSE-trending mylonites. A late timing ~~of~~for the E-W-trending structures is supported by the consistent offset of NNW-SSE-~~directed~~trending grain by E-W-~~directed~~trending structures throughout the WSB (Fig. 3).

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6.2 Summary of major deformation events affecting the WSB

Based on the new structural data presented in this paper and with reference to tectonic models proposed for surrounding areas (Wright, 1988; Talbot and Koyi, 1995; Bergman et al., 2001; Angvik, 2014; Skyttä et al., 2012; Andersson et al., 2017; Sarlus et al., 2017; Grigull et al., 2018; Luth et al., 2018; Lynch et al. 2018) ,), we propose the following tectonic model that utilizes two major deformation events for the WSB (Fig. 1821):

6.2.1 Pre-D_1- event

Syn-orogenic crustal thinning and mafic to felsic magmatism associated with backarc basin development has been inferred for the wider WSB-Kiruna area based on regional petrological/geochemical studies (Perdahl and Frietsch, 1993; Martinsson, 2004; Sarlus et al., 2017, 2018). The Orosirian stratigraphic record in the central Kiruna area (Fig. 1, 4) represents one of the best preserved, conformable Svecofennian supracrustal sequences in northern Norrbotten and comprises rock types that are correlative with those within the WSB. This suggests basin development at Kiruna was coeval with the deposition of the supracrustal rocks dominating the WSB (Andersson 2019). Based on this lithostratigraphic correlation, our deformation model for the WSB is predicated on that the area having initially developed within an extensional, basin-type setting that underwent subsequent compression and inversion.

6.2.2 D_1 event

NE-SW- to ESE-WNW-directed crustal shortening (this study; Wright, 1988; Talbot and Koyi, 1995; Lahtinen et al., 2005; Angvik, 2014),) that was coeval with syn-tectonic plutonism at 1.88-1.86 Ga (Bergman et al., 2001; Sarlus et al., 2017, Kathol, and Hellström 2018), generated ENE-verging, tight to isoclinal, shallowly NNW-plunging folds and a regionally distributed, consistently steep, WSW-dipping S_1 cleavage. This interpretation is mainly based on the F_1 fold patterns preserved in the Eustiljåkk area (Fig. 4). These fold structures could have formed in a fold-and-thrust belt (Wright, 1988; Talbot and Koyi, 1995; Angvik, 2014) or, alternatively, during basin inversion (Andersson et al. 2017). Crustal thinning during the emplacement of the volcanic rocks of the WSB has been inferred by petrological/geochemical studies (Perdahl and Frietsch, 1993; Martinsson, 2004; Sarlus et al., 2017, 2018) and assigned to a backarc basin developed during early Orosirian times (Sarlus et al. 2017,) generated ENE-verging, tight to isoclinal F_1 folds with shallowly NNW-plunging fold axes. A WSW-dipping axial planar S_1 cleavage/foliation, is locally associated with these F_1 folds in the WSB. 2018). Furthermore, the Orosirian stratigraphic record in central Kiruna area indicates the existence of a sub-basin formed in response to this extensional setting (Andersson et al. 2017).

Oblique-reverse dextral and sinistral shear zones with west-side-up sense-of-shear were developed during D_1 and produced the dominant NNW-SSE-alignedtrending, undulating, magnetic lineaments (Bergman et al., 2001) that characterize the WSB. The sense of shearing is based on SCC´ fabrics along shallow to moderately plunging stretching lineations (L_1) along the

NNW-SSE grain in the Ekströmsberg, Kaitum West and Fjällåsen-Allavaara areas. Activity (Fig. 3; Bergman et al., 2001). Deformation along these zones during D_1 is indicated by the presence of crenulated S_1 (Fig. 8e9e) and high-strain S_1-fabrics that are tightly folded in response to shearing alongby later D_2 shear bands parallel to the NNE-SSW structural grain (Fig. 12estructures (Fig. 13c-d). The strain was taken up by rheological/Strain partitioning appears to have been controlled by lithological contrastscontacts (or pre-existing discontinuities?), and favorable, incompetent?) as the highest strain is recorded by favourable, less competent lithologies such as volcanosedimentary rocks.

Based on the relatively steep dip of the NNW-SSE-aligned structural grain, and the syn-extensional geochemicalbroadly alkaline character of the affected volcanic rocks (Perdahl and Frietsch, 1993; Bergman, et al., 2001; Martinsson, 2004; Martinsson et al., 2016; Sarlus et al., 2017, 2018), and thewe favour a model involving inversion of an evolving backarc basin to account for D_1-related structures in the WSB. Backarc basin inversion took place under epidote-amphibolite metamorphic facies conditions (this study; Ros, 1979; Edfelt et al., 2005) as recorded by syn-tectonic growth of hornblende in albite + hornblende + epidote metamorphic textures in volumetrically minor Rhyacian pillow lavas in the Ekströmsberg area, we favor a model involving inversion of a backarc basin to account for D_1-related structures in the WSB. (Fig. 16a-c). This contrasts with models that envisage the development of a classic fold-and-thrust belt in the broader WSB and -Kiruna area during D_1 (Wright, 1988; Talbot and Koyi, 1995). Consistent evidence for the rotation of originally shallow-dipping thrust-type structures into sub-vertical orientations was not found along the WSB. Such a model was favored by Wright (1988) and rejected by Bergman et al. (2001). Furthermore, no classic fold-thrust beltsbelt features involving shallow thrusts and/or nappe stacks have been identified in nearby areas (Vollmer et al., 1984; Wright, 1988; Talbot and Koyi, 1995; Grigull et al., 2018; Luth et al., 2018). However, Angvik (2014) identified a series of fold-thrust belts in the Rombak Teconic Window, west of the WSB in Norway. It is possible that the Rombak Tectonic Window represents a fundamentally different setting within the same volcanic arc environment and that the change from a classic fold-thrust belt to an extensional back-arc setting is to be found in between the WSB and the Rombak Tectonic Window.

6.2.23 D_2- event

A phase of cac. E-W compression caused meso- to macro-scale folding of S_1 foliationsfoliation and produced near-cylindrical, upright and steeplyF_2 folds with steep N- and S-plunging F_2 folds. Similarfold axes. Broadly similar F_2 folding fold characteristics are developed in all key areas throughout the WSB. Based on the general lack of axial planar-parallel S_2-cleavages, we suggest that D_2-related folding took place at relatively shallow crustal levels and/or low-pressure shortening conditions (Pfiffner, 2017).

Strong strain partitioning focused D_2-related deformation into pre-existing NNW-SSE-aligned D_1-trending oblique-slip D_1 shear zones causing their reactivation with a reverse dip-slip, west-side-up sense-of-shear. Synchronously, near vertical E-W directed trending sinistral (and possibly dextral?:; Wright, 1988) brittle-ductileplastic strike-slip shear zones were active and locally off-set the NNW-SSE structural grain. Applying a basin inversion model to the WSB implies that the E-W directed

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structures might have originated as transfer faults between NNW-SSE--trending normal faults and that the combined structural configuration was reactivated together, first during D_1 and later during D_2.

D_2-related kinematics are based on SC fabrics observed along steep- to near-vertical plunging L_2 stretching lineations within NNW-SSE-trending high-strain zones at Ekströmsberg, north of Kaitum West and the Fjällåsen-Allavaara areas, and. Correlative microstructures are also -along observed within shallowly E-plunging stretching lineations fromin E-W-trending high-strain zones inat the Ekströmsberg area. The E-W-directed offset of NNW-SSE-trending high-strain zones is interpreted from magnetic maps (Frietsch et al., 1974; Bergman et al., 2001). Joints and fracture planes pre-date the latest epidote alteration in the area and are interpreted as developed either during D_2 or slightly afterthereafter.

6.3 Timing of D_1-D_2 deformation within the WSB, and comparative links with adjacent areas

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Tectonic models for northern Norrbotten and the Skellefte district generally include an early phase of deformation at approx. 1.88-1.86 Ga (e.g. Wright, 1988; Talbot and Koyi, 1995; Lahtinen et al., 2005; Skyttä et. al., 2012; Angvik, 2014). In the Skellefte district, the minimum timing of crustal shortening with related folding and shearing was constrained to 1.87 Gaat 1874 ± 4 Ma (Skyttä et al., 2012), which is comparable to the 1895 Ma - 1877 Ma maximum age ofages at 1888 ± 7 Ma and 1865 ± 8 Ma for NNW-SSE-trending shear zones and related 1886 Ma - 1837 Ma Au-Cu mineralization in the Kautokeino Greenstone belt north of the WSB in Norway (Bingen et al., 2015, Henderson et al., 2015). In accordance with). Similarly to this studystudy's interpretation, Allen et al. (1996), Bauer et al. (2011), and Skyttä et al. (2012) indicatedproposed that the shear zones in the Skellefte district formed during a phase of continental arc- extension and volcanic activity prior to 1.88 Ga, and were subsequently reactivated during thec. 1.87 Ga accretion of the arc onto the Archean continent and relatedsubsequent crustal shortening. Alternatively, in the West Troms Basement Complex some 250 km northwest of the WSB, Bergh et al. (2010) record no evidence of 1.88-1.86 Ga deformation, but instead a pronounced ductile footprint developed at 1.80-1.75 Ga in response to NE-SW shortening.

Overall, the interpreted early history of the NNW-SSE tectonic grain in this study is similar to structural mapping results from the Skellefte district further south (Skyttä et al., 2012) where an approx. N-S-directed crustal shortening (D_2 in Skyttä et al., 2012) was constrained to 1.87 Ga by SIMS U-Pb zircon dating. Such a timing of D_1 (D_2 in Skyttä et al., 2012) would harmonize well with our interpretation of D_1 as synchronously with the plutonic rocks (1.88-1.86: Bergman et al. 2001) boarding the WSB.

In terms of later deformation events, Bauer et al. (2016) and Lynch et al. (2018) report west-side-up movements during a D_2 phase of deformation in the Cu-Au-mineralized Nautanen Deformation Zone (NDZ) near Gällivare, which generated a duplex Riedel-shear system within that composite zone. Additionally, Bauer et al. (2018) argue for E-W compression during a D_2 phase of deformation and link this event to the intrusion of 1.8 Ga syn-tectonic minimum melt granites (e.g. Öhlander et al., 1987; Bergman et al., 2001; Sarlus et al., 2017). The results from the NDZ agree with results from A similar timing of deformation is interpreted for the Rombak Tectonic Window (Angvik, 2014) ca.c. 100 km west of the WSB. in Norway where U-Pb zircon ages for syn-tectonic granites (Angvik (, 2014) brackets the timing of a comparable deformation event (D_3-D_4 in

Angvik, 2014) between 1778 Ma and 1798 Ma based on U-Pb zircon ages for syn-tectonic granites(D$_3$-D$_4$ in Angvik, 2014) . Based on the above studies, we suggest a similar timing for D$_2$ in this study, which includes folding, reverse dip-slip reactivation of NNW-SSE-directed D$_1$ shear zones, and strike-slip shearing along E-W directed brittle-plastic structures under brittle-ductile conditions.(see Section 6.2 above).

6.4 Hydrothermal alteration and metamorphism and its relationship to deformational events

A preferentially aligned hornblende + epidote + plagioclase assemblagemineral association defines the S$_1$ continuous cleavagecleavages in Rhyacian metabasaltsmafic volcanic rocks in the Ekströmsberg area (Fig. 15e17g). A similar mineral assemblageassociation was used by Ros (1979) and Edfelt et al. (2005) to define the metamorphic grade affecting mafic rocks in the Tjårrojåkka area (Fig. 2, 3, 910). According to Spear (1993), hornblende + epidote + plagioclase would indicate a transition from greenschist to amphibolite facies metamorphic conditions. Similarly, we interpret the hornblende + epidote + plagioclase assemblageassociation as a key metamorphic indicator assemblagemineral association (Ros, 1979; Edfelt et al., (2005)), which accords with the generally accepted, but poorly constrained, low- to medium-grade low-P regional metamorphism of northern Norrbotten (e.g. Frietsch et al., 1997; Bergman et al., 2001; Skelton et al., 2018). In Figure 15g16a, the hornblende + epidote + plagioclase S$_1$-fabric forms axial planes to a folded hornblende + epidote vein-fill and, which possibly indicates a hydrothermal origin and pre-compressional timing for some hornblende + epidote. F$_1$-folded and thus a pre-D$_1$ commencement of prograde metamorphism. However, hornblende veins with axial planar-parallel S$_1$ foliation have also been observed in the Fjällåsen-Allavaara areathis vein displays syn-tectonic characteristics (Fig. 14a, d).16b, c) implying that metamorphism probably peaked during the fabric-forming D$_1$-event.

Regional scapolite alteration in northern Norrbotten is thought to be linked to the formation of IOA and Cu-Au deposits there, having formed due to the activity of relatively high salinity ore-forming fluids (Martinsson et al., 2016). In this respect, the widespread albite + scapolite alteration in the WSB may partly represent the effects of hydrothermal fluid flow associated with the formation of IOA and Cu-Au mineralization in the area. Several generations of albite + scapolite alteration are present throughout the WSB. The and in differing settings. For example, the porphyroblastic and the semi-conformable (selectively pervasive) types (Fig. 15a, b17a, c) are commonly encountered in low strain blocks close to shear zones or in mafic dykes within or at the margins of meter-wide shear zones. Scapolite porhyroblasts are often undeformed and tend to overprint early D$_1$-fabrics. Hence, we infer the timing of the regional porphyroblastic scapolite formation as syn- to late-D$_1$. This inference is broadly consistent with a metasomatic (titanite) age of ca 1.9 Ga reported for a scapolite-altered mafic dyke that forms part of a Rhyacian greenstone sequence in the Nunasvaara area of central north-central Norrbotten (Smith et al., 2009). In the NDZ to the east of the study area, Lynch et al. (2015) report early sericite + scapolite + feldspar, which is probably representing the same regional alteration event. Local, late and discordant occurrences of scapolite, mainly in veins and shear bands, frequently occur proximal to the early scapolite. This discordant scapolite probably represents remobilization of the early albite + scapolite during possible D$_2$-related deformation which would support recycling of chlorine in northern Norrbotten as suggested by Bernal et al. (2017). Stable Br/Cl ratios of scapolite altered rocks in northern Norrbotten plot in the magmatic field and suggest

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a mainly igneous fluid source (Martinsson et almetasomatic (titanite) U/Pb ages at 1851 ± 6 Ma and 1850 ± 7 Ma reported for a scapolite-altered diorite east of the WSB (Martinsson et al. 2016). However, at the same locality, Smith et al. (2009) reported 1903 ± 8 Ma for scapolitization, which indicates that scapolite alteration in the Norrbotten area is likely polyphase and occurs as several generations.., 2016). However, several studies have postulated that scapolite occurrences in lower Rhyacian greenstones might represent former evaporate beds (Frietsch et al., 1997; Martinsson, 1997; Bernal et al., 2017). Nevertheless, due to a spatial relationship with 1.88-1.86 Ga monzonite (shoshonitic) plutons and mafic volcanic rocks, regional scapolite alteration in northern Norrbotten has been attributed to have played a role in the formation of IOA and Cu-Au deposits (e.g. Frietsch et al., 1997; Martinsson et al., 2016).

Pervasive magnetite + amphibole + magnetite alteration (Fig. 15b, f17a, h) is commonly distributed in the WSB and probably of regional significance. Locally, it is locally overprinted and affected by both S_1 foliationsfoliation and paragenetically later alteration assemblages (Fig. 15f), hence, we attribute the timing of amphibole + magnetite alterationinterpreted as early- to syn-D_1. Pervasive amphibole + magnetite occasionally shows an early timing relative to the more selectively pervasive albite + scapolite alteration (Fig. 15b), although we have also observed the opposite relationship. In this context, the possibility that both assemblages represent an evolving calcic-sodic-ferroan alteration system similar to that suggested in other analogous IOA-IOCG-mineralized terranes may also be valid (e.g. Corriveau et al., 2016; Montreuil et al., 2016 a, b). Similar crosscutting relationships have been documented in the Cu-Au-mineralized NDZ near Gällivare (Lynch et al., 2015), although Lynch et al. (2015) included biotite as part of an selectively pervasive amphibole + magnetite alteration assemblage. Amphibole + magnetite alteration also occurs as discordant veins with albite haloes (Fig. 15c17b). The relative timing of these veins is difficult to resolve due to the lack of an association with other discernablediscernible tectonic structures, but we tentatively assign a D_1 timing and a paragenetic link with the pervasive amphibole + magnetite assemblageassociation based on their similar mineralogy and often close spatial relationship.

Regional selectively pervasive (patchy) K-feldspar alteration (replacing albite) is an important component in the felsic volcanic rocks of the WSB (Fig. 15g, h). It was documented already during the (see Fig. 19). Pervasive amphibole + magnetite occasionally shows an early timing relative to the early mapping campaigns in the area (Offerberg, 1967) selectively pervasive albite + scapolite alteration (Fig. 17a). However, we have also observed the opposite relationship between pervasive magnetite + amphibole and early selectively pervasive albite + scapolite alteration. Thus, the possibility that both hydrothermal mineral associations represent an evolving calcic-sodic-ferroan alteration system similar to that suggested from other analogous IOA-IOCG-mineralized terranes (e.g. Corriveau et al., 2016; Montreuil et al., 2016 a, bis often accompanied by retrograde sericite and epidote. Development of selectively pervasive K-feldspar) is possible. However, in the WSB, a clear spatial zonation of hydrothermal alteration at the exposed surface has a late timing relative to D_1-related deformation, hence,not been observed (e.g. Fig. 18) but it is assignedpossible that such a zonation is masked by overburden.

The hydrothermal mineral associations linked to D_2 in this study is potassic-ferroan in character and in most cases is hosted by D_2-structures. A late D_2-timing is interpreted for the biotite + magnetite + K-feldspar + muscovite alteration hosted by sinistral E-W shear zones near the NNW-SSE-trending Ekströmsberg IOA deposit (Fig. 17k, l). A late D_2 timing for this potassic-ferroan alteration is evident by offsetting relationships between the E-W structural grain and more dominant NNW-SSE-trending D_1-fabrics. Paragenetically late and structurally controlled potassic alteration associated to epidote occurs along volcanosedimentary bedding (Fig. 17g, 19) or as vein-fills associated to iron oxides and sulfide crosscutting magnetite-amphibole alteration in outcrop-scale (Fig. 17h). In the Tjårrojåkka area, Edfelt et al. D_2-timing in this study. Local vein-fill K-feldspar alteration is rather common and is sporadically overprinted by epidote, iron oxides and sulphide (Fig. 15f). In the Tjårrojåkka area, Edfelt et al. (2005) suggest(2005) suggests K-feldspar alteration is paragenetically late relative to scapolite. Similarly, in the Gällivare area, K-feldspar alteration shows a late D_2-timing and a close spatial relation to c. 1.8 Ga granitesgranite and pegmatitespegmatite (Bauer et al., 2018), hence in agreement with our observations from the WSB.

Locally, late stage calcite associated to rare sulfide mineralization forms part of (Fig. 17e) or overprints (Fig. 17f) D_2-shear zone fabrics in structures intersecting mafic rocks. Late stage carbonate deposition has been described for magnetite group IOCG in the Cloncurry-district in Australia (Corriveau and Mumin 2010) as well as in Norrbotten close to Kiruna (Fig. 1), where carbonates are associated to sulfides in a discordant albite-carbonate mylonite zone (Bergman et al. 2001). A late D_2-timing is also interpreted for the biotite + magnetite + K-feldspar alteration hosted by sinistral E-W shear zones near the NNW-SSE-aligned Ekströmsberg IOA deposit (Fig. 15i, j). A late D_2-timing of this potassic-ferroan alteration is evident by off-setting relationships between the E-W structural grain and more dominant NNW-SSE-aligned D_1-related fabrics. Magnetite in this shear band-hosted mineral assemblage may be locally remobilized from the IOA deposit, although further in-detail analytical studies are required.

The mineral It is possible that the late-stage carbonate alteration reported in this study forms part of a larger ore-forming system during D_2. However, in the case where carbonate alteration overprints D_2 shear zone fabrics (Fig. 17f), the possibility that ingress of retrograde meteoric fluid depositing carbonate during down-welling as described by Kesler (2005) cannot be excluded at this stage of research.

Hydrothermal alteration with an inferred D_2-timing that does not show a direct association with tectonic structures is regional selectively pervasive (patchy) K-feldspar alteration (replacing albite), often accompanied by sericite and epidote. This is an important alteration component in the felsic volcanic rocks of the WSB (Fig. 17k) and it was documented already during the early mapping campaigns in the area (Offerberg, 1967). Few crosscutting relationships exists for this type of alteration, however, fracture planes carrying epidote (Fig. 17i) postdate this selectively pervasive K-feldspar alteration implying the latter developed before brittle deformation and probably syn- to late-D_2 and broadly coeval with the structurally controlled potassic mineral associations occurring along the WSB.

The spatial distribution of identified hydrothermal mineral associations and their spatial correlation to dominant structures is summarized on the map in Figure 18. The map shows that D_1-related mineral associations are confined to geological structures and also overprint areas distal to dominant D_1 structures. Overall, scapolite ± albite is more widespread than magnetite + amphibole alteration. The intensity of potassic alteration seem to decrease towards the north, which can be explained by the general absence of c. 1.8 Ga granites in that part of the WSB. Carbonate alteration is confined to structures with an inferred D_2-timing. Distribution uncertainties for the alteration associations shown in Figure 18 are high due to the scattered nature of the observations and the glacial till covering most of the WSB.

The alteration styles identified throughout the WSB may represent important vectors for both IOA~~-~~ and IOCG~~-deposits~~ mineralization along the belt, in northern Norrbotten (e.g. Martinsson et al., 2016) and world-wide (e.g. Corrieveau and Mumin, 2012). In our study, alteration styles typical for comparable IOA-IOCG districts elsewhere (i.e. calcic-sodic and potassic ± ferroan ~~assemblages~~associations) are consistently developed along the WSB and show a spatial association with certain generations of structures that can be correlated with the position of known IOA- and/or IOCG-style mineralization (e.g. the Ekströmsberg and Tjårrojåkka areas; Fig. 18).

6.4.1 Summary of hydrothermal ~~alterations~~alteration, metamorphism, and ~~its~~their relation to deformation

To summarize the relative timing of the ~~dominant~~various alteration styles and how they relate to Orosirian magmatism and mineralization in the WSB and northern Norrbotten in general, a summary sketch in Figure 19 and the following ~~scheme is~~ key points are presented ~~(Fig. 16): Peak metamorphism is indicated~~based on this study's results, combined with stratigraphic and geochronology data reported by ~~hornblende +~~ Romer, et al., (1994); Bergman, et al., (2001); Wanhainen, et al., (2005); Edfelt, (2007); Smith et al., (2009); Westhues et al., (2016); Martinsson, et al. (2016); Sarlus, et al., (2017); and Bergman, (2018):

D_1:

- Emplacement of calc-alkaline intrusions (Haparanda suite) and coeval volcanic rocks (Porphyrite group) as well as pre- to early-D_1 in northern Norrbotten.
- Porphyry copper formation east of WSB pre- to early-D_1.
- Emplacement of mildly alkaline intrusions (Perthite-monzonite suite) and coeval volcanic rocks (Kiirunavaara group) pre- to syn-D_1 in northern Norrbotten.
- IOA mineralization east of the WSB (in central Kiruna) during pre- to early-D_1.
- Regional pervasive amphibole + magnetite alteration in the WSB early- to syn-D_1.
- Discordant vein fill amphibole + magnetite + albite alteration early- to syn-D_1.
- Metamorphic peak in the WSB (epidote~~ + albite implying upper greenshist to lower -~~amphibolite facies metamorphism) syn-D_1 (earlier metamorphic onset as well as prolonged metamorphic conditions ~~around the Ekströmsberg area. The timing of peak metamorphism is interpreted as early to syn-D_1.~~is possible).

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~~D_1 is related to the following hydrothermal/metasomatic mineral assemblages:~~

- ~~Regional conformable~~Conformable albite-scapolite alteration or growth of albite-scapolite porphyroblasts in the WSB syn- to late-D_1.
- ~~Regional pervasive amphibole + magnetite alteration.~~
- ~~Discordant vein fill amphibole + magnetite + albite alteration.~~

- IOCG mineralization east of WSB during late D_1.
- Shear zone hosted pervasive actinolite + tremolite alteration late-D_1.

D_2 is related to the following mineral alteration assemblages:

- Regional selectively pervasiveCalcite in veins with unknown temporal relation to D_1 but pre-D_2.
- Scapolite in veins with unknown temporal relation to D_1 but pre-D_2.

D_2:

- Emplacement of Lina and Edefors intrusive suites in northern Norrbotten syn-D_2.
- IOCG mineralization confined to shear zones east of WSB syn-D_2.
- Local shear band-hosted biotite + magnetite + K-feldspar alteration in the WSB syn-D_2.
- Local discordant vein fill-hosted K-feldspar + epidote + iron oxide + sulphidesulfide alteration syn-D_2.
- Local discordant vein/shear band fill scapolite alteration syn-D_2.
- Local shear band fill of biotite + magnetite +IOA and IOCG emplacement in the Tjårrojåkka area (WSB) late-D_2.
- Calcite alteration syn- and- late- to post-D_2.
- Regional selectively pervasive K-feldspar alteration syn- to post-D_2.
- Local fracture-fill epidote alteration post-D_2.
- Retrograde sericite alteration post-D_2.

7 Conclusions

Based on the new structural mapping and microstructural investigationsinvestigation presented in this study, two major compressional events affecting the Western Supracrustal Belt (WSB) in northwestern Norrbotten have been identified. These deformation events, D_1 and D_2, developed a pronounced structural signature and, corresponding structures which can be correlated with different types of mineral alteration assemblages. Early D_1 produced a steep SW- to WSW-dipping heterogeneously developed penetrative and continuous S_1 foliation related to F_1 folds with either tight east-verging symmetries with a shallow NW-plunge or tight upright symmetries with steep plunges. The steep F_1-plunges are in this paper interpreted to be a result of later D_2-transpositionassociations within the belt. Shear zones recording reverse oblique west-side-up kinematics were developed during D_1 giving rise to an undulating NNW-trending configuration of magnetic lineaments. D_1 produced a steep SW- to WSW-dipping, heterogeneously developed, penetrative and continuous S_1 foliation related to F_1 folds with either tight, east-verging symmetry with a shallow NW-plunging fold axis, or tight upright symmetry with steep fold axes. Steep plunges of F_1 fold axes are interpreted to be a result of later D_2-transposition.

The S_1 foliation was folded during D_2 into near-cylindrical F_2 folds with steep N- and S-plunges.plunging fold axes. Axial plane parallelplanar S_2 foliation isfoliations are rarely developed in relation to thesewith F_2 folds and whenwhere present, S_2

is a spaced~~. The inability of D_2 to produce a tectonic foliation over large areas indicates that~~ cleavage in the ~~conditions during D_2 were of low-pressure type. Instead, the~~ cm- to several dm-scale. The finite D_2 strain was partitioned into pre-existing D_1 shear zones, ~~lithological contrasts, and rheologically favorable lithotypes,~~ reactivating these structures with reverse dip-slip west-side-up sense-of-shear. The D_2 strain was also partitioned into rheologically favourable lithotypes, such as volcanosedimentary rocks. Synchronously, E-W trending sinistral strike-slip shear zones were active and partly ~~displacing the~~ displaced earlier formed NNW-~~grain~~trending structural grains.

D_1 is associated with regional scapolite ± albite alteration ~~formed~~ that is broadly coeval with regional magnetite ± amphibole alteration ~~and calcite~~ under epidote-amphibolite ~~metamorphism.~~facies metamorphic conditions. The hydrothermal alteration ~~linked to the D_2 deformation phase~~ that affected rocks during D_2 is ~~more~~generally structurally controlled and potassic ± ferroan in character and dominated by K-feldspar ± epidote ± quartz ± biotite ± magnetite ± sericite ± ~~sulphides, and~~sulfides, as well as calcite. D_2 is also associated to ~~regional~~ selectively pervasive K-feldspar alteration ~~(~~replacing albite~~) and retrograde sericite and epidote but D_2 alteration is to a large extent characterized by being hosted by~~ , affecting intermediate to felsic rocks without any direct spatial correlation to structures. This implies that our field~~-~~based observations support an early D_1 timing ~~of~~for calcic-sodic alteration whereas a ~~late~~later timing (syn-D_2) is interpreted for potassic ± ferroan ~~style of~~ alteration ~~assemblages and~~associations. In absolute terms, the ~~time difference~~timing of these fluid-flow events may have ~~been~~differed by as much as c. 80 ~~m.y.~~million years based on previously reported geochronological ~~circumstantials reported~~ data from northern Norrbotten.

Data availability. Structural field measurements and analyzed thin sections are available from the corresponding author.

Author contributions. JBHA ~~performed the geological mappings within~~mapped the areas Eustiljåkk and eastern part of the Kaitum West. JBHA and TEB ~~performed the mappings of~~mapped the Ekströmsberg area and the areas in-between Ekströmsberg and Eustiljåkk. TEB and EPL ~~performed the mappings within~~mapped the areas Fjällåsen-Allavaara and Tjårrojåkka. JBHA, TEB, and EPL ~~did the mappings together of the western parts of~~mapped the Kaitum West area and the areas in-between Kaitum West and Ekströmsberg. JBHA ~~performed~~analysed the ~~structural analysis~~structures of Eustiljåkk, Ekströmsberg and Kaitum West. TEB ~~performed~~analysed the ~~structural analysis~~structures of the Tjårrojåkka and Fjällåsen-Allavaara areas. All microstructural analysis used in this paper was ~~performed~~done by JBHA. The writing was performed by JBHA with much help from EPL and TEB. Contributions are as follows: JBHA (50%), TEB (25%), EPL (25%).

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Figure 1: Generalized geology of northern Norrbotten highlighting ~~Palaeoproterozoic metasupracrustal~~Paleoproterozoic supracrustal belts. Simplified and modified after Bergman et al. (2001).

Figure 2: Geological map of the Western ~~supracrustal belt~~Supracrustal Belt showing the key areas ~~in relation to the belt~~mapped during this study. Lithological contacts simplified and modified after Offerberg (1967), Witschard (1975), and Bergman et al. (2001). Coordinates: Sweref99.

Figure 3: First vertical derivative, 150m upward continuation, aeromagnetic map of the Western ~~supra crustal belt overlaid~~Supracrustal Belt overlain by first vertical derivative ground-magnetic map of Ekströmsberg. The aeromagnetic data was collected using 200m line-spacing and 40m line down distance (Bergman et al. 2001). ~~(in Ekströmsberg).~~The ground-magnetic data was collected using ≤ 80m line-spacing and ≤ 20m down line distance (Frietsch et al. 1974). Outline of the key areas, observation

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points and dominant structures are the same as in Figure 2. ~~Red colour: magnetic high, Blue colour: Magnetic low. Magnetic data~~Data from Frietsch et al. (1974) and Bergman et al. (2001). Coordinates: Sweref99.

~~Figure 4~~Figure 4: Summary of the temporal relation between supracrustal/intrusive rocks, metamorphism, deformation, and mineralization in northern Norrbotten. Stratigraphic column of the supracrustal sequence relevant for this study is included.

Figure 5: Geological map of the Eustiljåkk key area. Modified after Offerberg (1967). Coordinates: Sweref99.

Figure ~~5~~6: Stereographic equal area projections highlighting A) Low strain S_1. B) High strain S-fabrics. C) Stretching and mineral lineations.

Figure ~~6~~7: Characteristics of Eustiljåkk key area. A) Low intensity S_1-foliation, X688743 Y7542711. B) Parasitic F_1 folding of ~~metasedimentary~~sedimentary horizons, X687043 Y7539378. C) Scapolite altered mafic dyke associated to N-S directed high strain zones, X687505 Y7543037. Coordinates: Sweref99.

Figure ~~7~~8: Geological map of the Ekströmsberg key area. Modified after Offerberg (1967). Coordinates: Sweref99.

Figure ~~8~~9: Field images and thin section photographs of characteristics of the Ekströmsberg area. A) Actinolite-tremolite L-tectonite overprinted by calcite alteration, X689886 Y7530423. B) Semi-conformable scapolite replacement of magmatic bedding in Rhyacian basalt, X688163 Y7530345 C) Magmatic bedding in a felsic volcanic rock resembling a weak tectonic cleavage in outcrop, X691591 Y7527763. D) Micrograph of the outcrop in Fig. ~~8C~~9C. E) Micrograph of crenulation from same locality as Fig. ~~8B~~9B, X688163 Y7530345. F) SCC´ fabric along north plunging stretching lineation in the NNW directed grain, X688714 Y7530350. G) SC fabric along near vertical stretching lineation in the NNW directed grain, X688167, Y7530354. H) SC fabric along shallow east plunging stretching lineation along the E-W directed grain, X690276 Y7527251. I) Brittle feldspar along the E-W directed grain, same location as Fig. ~~8I.~~9I. Scp: Scapolite. Coordinates: Sweref99.

Figure ~~9~~10: Geological map of the Tjårrojåkka key area. Modified after Offerberg (1967). Coordinates: Sweref99.

Figure ~~10~~11: Field images of key localities in the Tjårrojåkka key area. A) Isoclinal F_1 folding, X675916 Y7515915. B) Open chevron-style F_2 folding with spaced S_2, X676285 Y7516107. C) Open concentric F_2 folding with spaced S_2, X675985 Y7516176. Coordinates: Sweref99.

Figure ~~11~~12: Geological map of the Kaitum West key area. Modified after Offerberg (1967). Coordinates: Sweref99.

Figure ~~12~~13: Thin section and field images/sketches of key localities in the Kaitum West key area. A) Micrograph of S_0/S_1 composite fabric in volcanosedimentary rock, X698952 Y7505460. B) Isoclinal mesoscale folding of the S_0/S_1 fabric Fig. ~~12~~13 A. C) Volcanosedimentary unit showing a high strain cleavage sub-parallel to S_0. The S_0/S_1 fabric is transposed into the direction of D_2 shear bands, X700402 Y7504830. D) Simplified sketch of Fig. ~~12~~13 C. E) SC fabric and asymmetric dextral sigma-sigmoid viewed along shallow south-plunging stretching lineation, X702488 Y7504983. F) SC fabric indicating sinistral kinematics viewed along steep north-northwest-plunging stretching lineation, X693703 Y7519820. Coordinates: Sweref99.

Figure ~~13~~14: Geological map of the Fjällåsen-Allavaara key area. Modified after Witschard (1975). Coordinates: Sweref99.

Figure ~~14~~15: Field images of characteristics of the Fjällåsen-Allavaara key area. A) High intensity foliation, X721253 Y7473543. B) Isoclinally folded quartz and amphibole veins with related axial planar S_1 cleavage. Brittle-~~ductile~~plastic S_2 with dextral sense-of-shear, X721192 Y7473733. C) Tigh F_1 folding of S_0, X714642 Y7479559. D) Asymmetric lithic sigma clast viewed along steep north plunging stretching lineation, X715483 Y7478182 E) Isoclinal F_1 gently refolded by F_2, X713553 Y7480026. F) Gentle F_2 folding of S_0/S_1 with associated brittle-~~ductile~~plastic S_2, X721194 Y7473733. Coordinates: Sweref99.

~~Figure 15~~Figure 16: A) Albite + hornblende + epidote metamorphic fabric aligned axial planar S_1. Folded vein hosting hornblende + epidote. B) Syn-tectonic growth of hornblende C) Needle-shaped mineral forming traces of S1 in hornblende. All images from X690267 Y7529944, Ekströmsberg, Coordinates in Sweref99. Hbl: Hornblende, Ab: Albite, Epi: Epidote.

Figure 17: Field- and thin section images of alteration styles throughout the WSB. A) Scapolite + albite overprinting magnetite + amphibole, X695488 Y7507194, Kaitum West. B) Vein-hosted magnetite + amphibole with reddish albite haloes, X695459 Y7507412,

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Kaitum West. C) Scapolite porhyroblasts, X696049 Y7507684~~ B~~, Kaitum West. D) Scapolite in veins and patches transposed by later shear bands, X697177 Y7532766~~. C) Scapolite + albite overprinting magnetite + amphibole, X695488 Y7507194. D) Vein-hosted magnetite + amphibole with reddish albite haloes, X695459 Y7507412.~~, Vieto (see Fig. 2). E) Calcite overprinting actinolite-tremolite in L-tectonite in Fig. ~~8A~~9A. Calcite aligned with S_1/S_2 with undeformed granular epidote at grain boundaries, X689886 Y7530423~~.~~, Ekströmsberg. F) Reddish calcite overprinting ductile shear zone fabrics, X698369 Y7534383~~. G) Albite + hornblende + epidote metamorphic fabric aligned axial-planar parallel S_1. Folded vein-hosted hornblende + epidote, X690267 Y7529944.~~, Vieto (see Fig. 2). G) K-feldspar + epidote concentrated along volcanosedimentary bedding X721289 Y7471362, Fjällåsen-Allavaara. H) K-feldspar + epidote + Fe-oxide + ~~sulphide~~sulfide + malachite overprinting pervasive magnetite + amphibole, X694578 Y7506821~~. I) Selectively pervasive K-feldspar alteration accompanied by epidote, X696619 Y7508353. J) Selectively pervasive K-feldspar replacing albite in same outcrop as Fig. 8C, X691491 Y7527635. K~~, Kaitum West. I) E-W directed D_2-shear zone with magnetite bands, X690231 Y7527374~~. L~~, Ekströmsberg. J) Shear band hosted biotite + magnetite + quartz + K-feldspar + muscovite from the locality in Fig. ~~15K~~17l, Ekströmsberg. K) Selectively pervasive K-feldspar replacing albite in same outcrop as Fig. 9C, X691491 Y7527635, Ekströmsberg. L) Selectively pervasive K-feldspar alteration overprinted by epidote on a fracture plane, X696619 Y7508353, Kaitum West. Coordinates in Sweref99. Scp: Scapolite, Ab: Albite, Mag: Magnetite, Amp: Amphibole, Epi: Epidote, Cal: Calcite, Kfs: K-feldspar, Sul: Sulfide, Mus: Muscovite, Bt: Biotite.

~~Figure 16:~~ Figure 18: Geological map showing the spatial distribution of identified hydrothermal mineral associations and their relation to dominant structures and aeromagnetic anomalies. The map base on the observations performed in this study together with a compiled database of recorded alteration minerals at the Geological Survey of Sweden. Coordinates in Sweref99.

Figure 19: Summary of mineral alteration ~~assemblages~~associations in the WSB and their inferred timings and how this data relates to ages reported for supracrustal/intrusive rocks as well as mineralization in northern Norrbotten.

Figure ~~17~~20: Lower hemisphere equal area stereographic projections of lineation throughout the WSB. Cones represent 30° circles. A) L_1 Stretching- and mineral lineation measured on S_1 foliation planes in low strain blocks. B) Stretching and mineral lineation measured in high strain zones.

Figure ~~18~~21: Conceptual model of the structural development of the WSB.