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Solid Earth
Discussions

Interactive comment on "Fluid-mediated, brittle-ductile deformation at seismogenic depth: Part II – Stress history and fluid pressure variations in a shear zone in a nuclear waste repository (Olkiluoto Island, Finland)" *by* Francesca Prando et al.

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We thank the reviewer for his comments. It strikes us that he has not commented on the core data presented in the manuscript (the EBSD part) and on the resulting conceptual model of the fault. We are sorry that the reviewer thinks that the paper could not be read until its end, and we are happy to improve its quality, but at the same time, a review that does not address the main scientific content of the paper can only partially

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help us improve it. We accept the request to improve the clarity of the (first part of the) manuscript and we will modify it accordingly, but we feel that the reference to "... a larger study that has been cut and pasted in such a way as to reduce the length" is just a random and unsubstantiated accusation of plagiarism that we firmly reject. Please note that the iThenticate Similarity Report generated by Solid Earth upon submission of the manuscript reported a similarity index of 8%, and the report is available to the reviewers. Thus, there is no cut and paste whatsoever in this work. We also want to reiterate that this manuscript represents the Part II of a companion paper (Marchesini et al., SE 2019), so that a certain (and minimum) level of repetition in the geological setting and context of the study could be expected. This manuscript is the result of a PhD project, and the first author and all the co-authors have put a lot of effort into it. As always, we accept that we can do better and we look forward to addressing the reviews, as they certainly help us see the shortcomings of our work. At the same time, we would like to receive fair comments and not random accusations, in the spirit of a constructive scientific dialogue. In the following outline, we address the main comments of the reviewer, which are hinged on two main aspects: (1) a better explanation of the fault-zone structure, and (2) a re-evaluation of P-T estimates of deformation.

Geological Setting

The geological setting of the Olkiluoto basement in SW Finland has been summarized in a number of papers (Marchesini et al. 2019 and references therein) and detailed geological reports that are freely available from the POSIVA database (http://www.posiva.fi/en/databank#.XaWBNkxOJaQ). In this manuscript, we have drawn from all these sources to summarise the ductile and brittle deformation history of Olkiluoto. References to the tectonic evolution of southwest Finland are also presented in relation to the regional history of Olkiluoto. The reviewer requested more details on aspects of the geological setting that we feel are not directly relevant to the manuscript, such as the constraints on migmatite formation or the relationship between graben and greisen. Discussions on these aspects are published elsewhere, and to aid the interested readers we will add relevant references to some key literature on the subject. We will shorten and simplify the geological setting to omit details that are not directly relevant to our study. We will also clarify the relationship between the T of migmatisation (published in different studies) and our estimate of the T in the host rock from graphite thermometry (see our reply to comment on line 369).

Answers to specific comments:

Line 104: "the peak of high-grade metamorphism? Or early orogenic stages?" - Compared to the emplacement of tonalite and granodiorite at ca. 1.89-1.85 Ga, leucogranitic intrusions took place between ca. 1.86-1.79 Ga. This time range covers both the age of the peak metamorphism in Olkiluoto ($\sim$ 1.86-1.82Ga from Aaltonen et al., 2016 and reference therein) and the age for late stages of the Svecofennian orogeny ca 1.92-1.79 Ga, and is prior to the orogenic collapse that took plat at ca. 1.79-1.77 Ga, (Lahtinen et al. 2005, Korja et al. 2006) .To avoid confusion, we will refer only to the Olkiluoto regional evolution in the revised manuscript.

Line 104: "You are mixing several things here, be consistent" – Here we are reporting the ages of emplacement of leucogranites in the area while referring to the tectonic evolution. As stated above, in the revised text we will only discuss the Olkiluoto regional evolution.

Line 114 - yes, the brittle deformation history is polyphase and developed in the time span from 1.75 to 0.8 Ga (Mattila & Viola, 2014). We will omit the reference to brittle deformation history in line 114, as this is explained later in the text (line 125).

Line 118: "So the previous 2 events did not form under amphibolite facies conditions? How do you explain the migmatites?" – Mineral assemblages in the migmatitic rocks in Olkiluoto indicate peak metamorphism conditions at $\sim$ 3.7-4.2 Kbar and T >660° C (Tuisku and Karki, 2010). Cross cutting relationship between migmatites, tonalite/ granitic intrusions and D2 –D3 deformation structures locate the peak metamorphism between $\sim$1.86 and $\sim$1.82 Ga (Aaltonen at al., 2016 and reference therein), which

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corresponds to the age of D2 deformation. D3 deformation occurred under similar, but slightly lower, retrograded conditions under amphibolite facies (Aaltonen et al. 2016). Our study deals with structures formed during the D4 deformation stage that occurred during the retrograde metamorphism under greenschist facies conditions (Aaltonen et al. 2016). Here we describe the fabric and the deformation processes of D4 ductile structures, which represent the ductile precursors of brittle faults in the Olkilouto region (e.g. Skyttä & Torvela, 2018).

Line 124: We state that the onset of brittle deformation occurred at ∼1.75 Ga as discussed in Mattila and Viola (2014). However, we would like to note that this broad age is based on 40Ar/39Ar cooling ages of biotite in migmatites. The 40Ar/39Ar ages ranges between∼ 1.79- 1.72 Ga (Aaltonen at al. 2016), which would address the question of the time continuity between the ductile D4 deformation and the Stage I of brittle deformation. The suggestion for the beginning of brittle deformation is also in line with 40Ar/39Ar dating of shear zones from southern Finland (Torvela & Ehlers 2010) and rock samples from the Forsmark region in central Sweden (Söderlund et al. 2009). To increase clarity, we will mention this point in the revised manuscript.

Line 130: “Whats the basis for this? Please expand” – Not all details of the complex structural evolution of Olkiluoto can be attributed to specific processes or tectonic stages of well-defined age, even though several studies have contributed to better characterise the area. For southern Finland, exhumation during the 1.81-1.79 Gyr interval has been proposed by several authors (e.g., Lahtinen, 2005; Vaisanen et al., 2000; Korsman et al., 1999), although the relative contributions of tectonic and erosional processes remains unclear . The rapakivi granites of southern Finland are believed to have emplaced under pressure conditions of 1-3.5 kbar (Eklund & Shebanov 1999), i.e. at a depth of ca 4-14 km (assuming a crustal density of 2500 kg/m3). Considering the known pressure conditions during peak metamorphism at Olkiluoto (3.7-4.2 kbar (i.e. 15-17 km) approximately 1.86 Gyr ago), one can conclude an average exhumation between 3 and 11 km during a time span of ca. 300 Ma, i.e. an exhumation rate of approximately 10-40 m/Ma. Although we ignore the exact geothermal gradient during the early phases of the evolution of the crust at Olkiluoto, onset of brittle deformation between 1.79-1.72 Ga suggests that at that time the present-day surface was not deeper than 10 km (a depth that is generally considered as the transition between the brittle and ductile regimes). This would indicate slightly higher exhumation rates in the early phase, ca. 5-7 km during a time span of 70-120 Ma, i.e. 40 m/Ma - 100 m/Ma and lower exhumation rates of 25-40 m/Ma for the time period between 1.79-1.72 Ga and 1.56 Ga.

Line 142: "This should have probably been described above. I dont know how this information helps with the role of fault localization" – After the summary of the ductile and brittle deformation history of the area, here we report the observation that brittle faults commonly exploit localized shear zone in Olkilouto, as described in detail in Skyttä & Torvela (2018). This observation has been widely reported in the literature (e.g. Massironi et al. 2011 and references therein) and our own observations are entirely consistent with, and certainly do nothing to contradict, this. One of the goals of our work is to derive a conceptual model of the fault zone behaviour across this progressive transition from dominantly ductile to brittle deformation.

Line 147: "This is all very well, but can you categorically confirm that this is as a result of progressive strain localization? After all it's a proposition" – We believe that our data confirm that this is the result of progressive deformation of the shear zone under constant kinematics (sinistral strike slip) and during cooling and exhumation. We have not done any geochronology work so that we cannot be more specific on the ca. 40 Ma gap between D4 (1.81 – 1.79 Ga) and the onset of brittle deformation at $\sim$1.75 (see above comment on line 124). Even if the ductile deformation ceased at 1.79 and brittle deformation took over at 1.75 Ma, (1) brittle deformation localised on a ductile precursor, (2) brittle and ductile deformation have the same kinematics, and (3) brittle deformation occurred under lower T conditions than ductile deformation. All of this is consistent with progressive deformation of a shear zone from overall ductile to overall brittle deformation, and we do not see any problem if this progressive deformation had periods of tectonic quiescence.

Results – BFZ045 fault zone structure and microstructures

Our study is based on two sections of drill cores, and we approached the description of the fault zone based on the first observed occurrence of specific structures (e.g. joints, veins) and fault rocks (e.g. mylonites, cataclasites) along the cores. This has led us to the description of brittle structures, such as the damage zone in the host rock, before ductile structure located in the fault core, as the thickness of the brittle damage zone is larger than that of the mylonitic precursor of the fault. However, since a description of the composite fault rock assemblage based on spatial occurrence seems to have caused confusion to the reviewer, we will be clearer in the revised text.

Answer to specific comments:

Line 208: “OK, here is where you have to help the reader develop a clear picture of the fault zone geometry. As I understand, you have a damage zone that is ∼0-5 m thick, and the fracture density increases towards the fault. OK when did this happen? Then you have a mylonite zone, how does it fit into the picture? I can't see how the damage zone is related to the mylonite zone, after all the former is brittle and the latter is ductile. Then you have damaged zones in the mylonite zone. Are these related to the damage zone? If not, why. As it stands, I can't really get a clear picture of what is going on.” - The brittle fault zone BFZ045 exploits a mylonitic precursor. The 0.5 m (0-5 m is a typo, it should be 0.5m) thick damage zone and the associated increase of fracture density towards the fault core are both related to the brittle deformation. Our interpretation is that the brittle fault (by which we mean the brittle core made up of cataclasites, gouges and pseudotachylytes) represents the last stage of evolution of a shear zone that progressively narrowed during exhumation. What we see now, is the composite fault rock assemblage with overprinting relationships resulting from the dominant mylonitic deformation at depth of ca- 12-14 km progressively overprinted by brittle deformation at depth of ca. 9-11 km. The mylonite represents an earlier history of the long-lasting ductile-brittle deformation history of BFZ045. Even the overall 'ductile' part of the history was punctuated by transient brittle events in the form of quartz veins that were subsequently mylonitised under a constant kinematic regime (sinistral strike slip). We reiterate here that by "damage zone" we intend the brittle damage zone associated with the brittle part of the history, when the mylonitic foliation was finally overprinted by cataclasites and pseudotachylytes. Cataclasites and pseudotachylytes are not mylonitised, and for this reason we interpret them as forming when the fault was at shallower, colder, crustal levels. In summary, the damage zone is not related to the mylonite, but only to the brittle fault core (the mylonite is just passively overprinted by the damage zone, as it had stopped working when the damage zone developed). This is consistent with the standard use of the term "damage zone" in structural geology, and we will further clarify this in the revised text. We will improve the microstructural description of the fault rocks by introducing clearer subheadings (host rock, mylonite, cataclasite) instead of damage zone (e.g. 4.3.1).

Line 298: "Are the boundaries of these veins localizing cataclastic deformation? If not I would not really describe different features associated with mylonitic deformation with the cataclasite" – See our answer above – we will introduce clearer subheadings to better separate between the mylonite (with the veins) and the cataclasite microstructures. Please note that the distribution of mylonitised veins in close proximity to the cataclasite is an important observation, because the recrystallized grain size of quartz in the veins indicates a localised progressive increase in stress and strain rate, which, in our view, culminated in the generation of cataclasites.

Results – P-T conditions of deformation

Line 369: "So it looks like graphite is associated with chlorite. So, what do you mean by peak metamorphic temp for the carbonaceous material. Sample PH21-1 is a fair way away from the mylonite zone, and if anything, I would assume that chlorite & graphite in the host rock must be associated with some late introduction of fluids, probably related

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to brittle fracture or at the earliest syn mylonitization. If its the latter, how do you link the graphite in the host rock with the graphite in the mylonite?" – With "peak metamorphic temperature for the carbonaceous material" we meant to indicate the highest temperature occurring during graphite crystallization. We are aware that such a temperature estimate is not consistent with the peak metamorphic temperature of Olkiluoto, and we will clarify this in the revised text. The raman spectra for the graphite of the host rock is not representative of well crystallized graphite for T> 600° C (Kouketsu et al., 2014), which we would have if it crystallized during the migmatisation (See Fig. 1). Whilst we cannot be certain of the timing of crystallization of the graphite, its textural position in the mylonite (parallel to the foliation) suggests a syn-kinematic formation. We link the graphite in the host rock to the mylonite through the temperatures, which indicate and overall retrogressive evolution. We agree with the reviewer that the graphite in the host rock is presumably associated with some introduction of fluid, and we interpret this to have occurred during the progressive evolution (and cooling) from D3 to D4, which culminated in strain localization at around 400-450° C in D4 mylonites like the one described here. If the graphite observed in the host rock were related to late brittle fractures we should have obtained lower temperature estimates than 500°. We decided to present the results for graphite in the host rock in order to rule out a temperature underestimation due the effect of deformation (Kirilova et al., 2017), as discussed in the methods section of the manuscript (3.2). Line 370: "a slightly lower ...In reality, the two temperatures are within error of one another. Are the errors 1 or 2 sigma? The error presented are 2 sigma.

Line 372: "I dont like you table with the compositions of minerals. Averages are useless. What you should do is present representative analyses and then you can then refer to the whole data table." – We will reformat our tables in the way that the reviewer likes, with representative analyses. We note that the whole data table is already included in the submission.

Line 374: "The composition of white mica was determined in areas where it is in contact with K-feldspar. Explain rationale here.” – the rationale is that the application of the phengite barometer requires stability of Kfs, we will add this to the text.

Line 376: “So I think we have a problem here. Feldspar is recrystalizing in the mylonite, which would suggest a T of ∼500°C. So why use 440°C. Again” - This is probably an incomplete comment, as we do not understand what should be read after “again”. We did observe feldspar neoblasts in the mylonite, but we never mentioned that they formed by dynamic recrystallization, this was an assumption made by the reviewer (line 256). Anyway, there isn't any problem here at all. It is crystal plasticity and recovery in feldspar that normally require T of ∼500°C, not the presence of neoblasts of feldspars along a foliation. This is a common misconception that makes people to often over-estimate the T of deformation based on the occurrence of neoblasts of feldspars in a mylonite. The reviewer is correct that dynamic recrystallization (by subgrain rotation for example) and efficient recovery in feldspar normally requires T of at least 500°C. But this is different from neocrystallisation, by e.g. dissolution-precipitation processes or growth from fractured fragments. These processes can be active in feldspars even at greenschist facies conditions, as consistently demonstrated in a number of studies (Fitz Gerald and Stünitz 1993; Menegon et al. 2008; Eberlei et al., 2014; Torgersen et al., 2015;Hentschel et al., 2019). Thus the stability of feldspar along the mylonitic foliation does not require T in excess of 500°C and does not invalidate our estimate of 440°C derived from graphite thermometry in the mylonite.

Line 390: “You can't really just give the averages without also quoting the SD. The range of T's in the chlorite veins is quite considerable and you could argue that the information is inconclusive. There is a population at high-T of ∼460 and one at lower T of ∼350.” – We will add the standard deviation to the text and figures. For the mylonite Tavg= 440° C (28 SD); for the cataclasite Tavg= 414° C (48 SD); and for the veins Tavg= 424° C (57 SD). In the veins the range is indeed quite considerable, but we could not observe any obvious textural differences in the chlorites that could help differentiate different populations in the veins. The broader range of T in the cataclasite and veins are interpreted as evidence of protracted formation of chlorite over a broad range of temperatures during cooling. Overall, the data indicates that chlorites in the mylonite belong to a higher T population compared to a (slightly) lower T in the veins and cataclasites.

Line 405: “OK, finally you spell out what is going on. I suggest that you reformat the manuscript in such a way that you describe the mylonites first and then the rocks associated with brittle deformation.”- We will improve the clarity of the presentation of the fault-zone structure, as discussed above.

Line 432: “OK, this is what was not clear to me above. It’s unlikely that the migmatites formed at temperatures of ∼530 °C. Migmatites typically start to form at T’s > ∼650°C at P’s of ∼3-4 kbar. In addition, I think you underestimate the T of mylonite formation as dynamic recrystallization of feldspar is typically assumed to be ∼500 °C. So overall, the T’s are essentially the same” –As stated above, the T obtained for the graphite in the host rock is not representative of the migmatisation, and feldspar dynamic recrystallization wasn’t observed in the mylonite. While we cannot exclude that the mylonite started to develop under temperature higher than∼ 450 °C, the temperature estimates of the graphite in the mylonite are consistent with an overall retrograde path. Moreover, previous studies constrained the D4 deformation under greenschist facies conditions (e.g. Skyttä and Torvela, 2018), and the BFZ045 mylonite of this study has orientation and mineral assemblage consistent with the structures normally attributed to D4 (Skyttä and Torvela, 2018)

Line 437: “As I mentioned above, the T’s slightly overlap within error” – The T of 440°C was chosen as it represents our best estimate of the temperature of mylonitization. Moreover as stated in the replies to previous comment, the graphite in the host rock is not representative of the migmatisation. In line 435 we suggest that graphite crystallization occurred after the D2 deformation phase (therefore after the metamorphic peak), which would be consistent with temperatures between 500-450 °C. As we cannot establish the age of graphite, we could assume a cyclic introduction of fluid associated with graphite crystallization, that occurred during the progressive cooling of the crust.

Line 459: “This is inconsistent with the overall thermal history you portray above” – We do not understand why this is inconsistent. These could represent fragments of mylonitic chlorite forming at T of ca. 450°C.

Line 462: “But this is happening during ductile deformation right? But you are describing the cataclasites, which formed at a much later date.” No, here we are comparing our findings with those of the companion paper. We estimated a T of around 400-500 for the ductile history of BFZ045, for which Marchesini et al estimated a minimum T of 350 in the conjugate fault.

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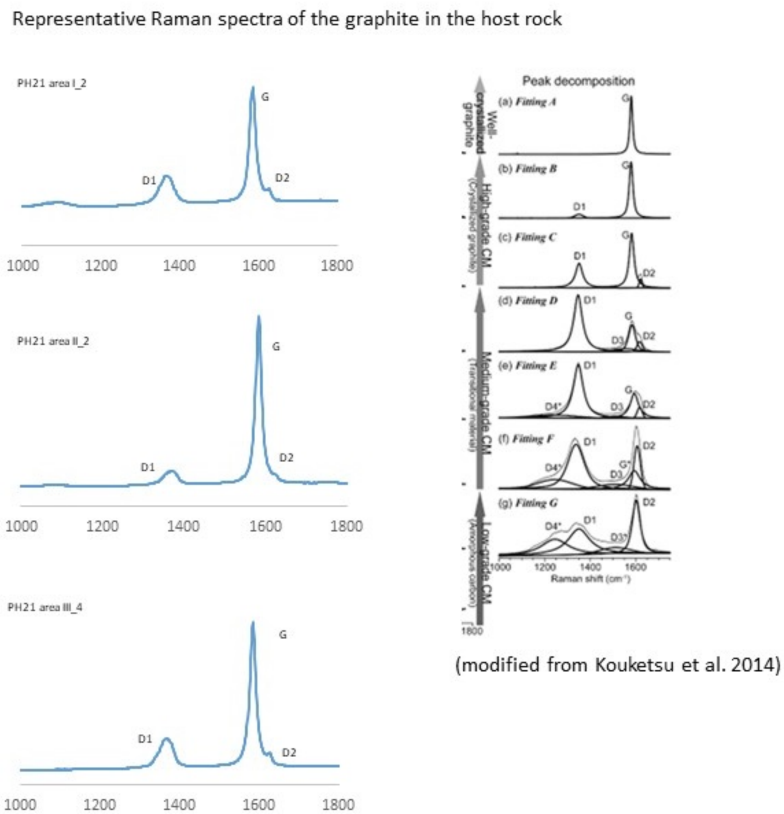

Fig. 1. Representative Graphite Raman spectra of BFZ045 host rock

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