Answers and responses to the comments of Topical Editor and Reviewers

Dear Editor,

Thanks for your comments. We have addressed all the outstanding points raised by the reviewers and by yourself, and this has resulted in some minor modifications to the manuscript, as requested. You can find our responses in the list here below, which starts from the comments raised by yourself.

We are looking forward to hearing your decision.

Kind regards,

Alberto Ceccato, Luca Menegon, Giorgio Pennacchioni, Luiz Morales

Comments to the Author:

Dear Dr Ceccato,

We have now received all outstanding reviews, please find them attached to this message. As Dr Menegon indicated in his email a few days back, you may wonder why I requested additional reviews after the first (generally positive) responses; this is because I find that the paper as such does not yet constitute a "substantial advance in the scientific understanding of the Solid Earth", as it should for publication as a research article in this journal (https://www.solid-earth.net/about/manuscript_types.html).

The significance of myrmekite has been highlighted by Dr Menegon and others in previous work, and the effects of reaction-induced softening and transition to GSS creep in mid-crustal shear zones are well-described. As is, I find that other, more specialized journals would be better hosts for your paper.

Response: *The novelty of our contribution was clearly stated in the introduction of the first version of the manuscript, "Though the key role of myrmekite in strain localization has been recognized, it has not been accompanied with a quantitative analysis of the deformation mechanisms within myrmekite-derived, fine-grained Plg + Qtz aggregates". The current paper provides an attempt to quantify the rheological effects of development of myrmekite during mylonitization based on a robust, modern microstructural analysis and on the determination of the deformation mechanisms in syn-kinematic monomyneralic and polymineralic aggregates. Such a quantitative estimate was not attempted yet in the many published studies on myrmekite in deformed rocks (e.g. LaTour and Barnett, 1987; Simpson and Wintsch, 1989; MacCaffrey, 1994; O'Hara et al., 1997; Tsurumi et al., 2003; Pennacchioni, 2005; Menegon et al., 2006; Pennacchioni and Zucchi, 2013; De Toni et al., 2016). To make the significance of our manuscript clearer in the advance of the scientific understanding of deformation of mid-crustal rocks we have now strengthened and expanded our original sentence in this last revised version.*

The fact that our manuscript potentially represents a substantial contribution to scientific progress within the scope of Solid Earth (substantial new concepts, ideas, methods, or data) is also recognized by the 4/5 referees who all scored this point ("substantial contribution ….") as GOOD and the importance of our contribution is also highlighted in the comments of some referees:
Referee #1 (first revision loop)" The descriptions of microstructures and textures of feldspars and quartz presented in this paper are robust, and discussion and conclusions are reliable and interesting.

This paper contributes to understand deformation process/mechanism of the mid-upper continental (felsic) crust."

Referee #2 (Elena Miranda): "This work is an important contribution to our understanding of how quartzofeldspathic rocks deform in the middle crust where the rheology-controlling minerals of the crust (quartz and feldspar) undergo a variety of deformation mechanisms that are aided by metamorphic reaction and reaction with fluids."

Referee #3 (James Gilgannon): "With the inclusion of the rheological discussion the authors provide the contribution with a rounded perspective. Specifically they advance our understanding by applying the results of laboratory and theoretical works to a natural example. This links the microstructural analysis to the current understanding of the physics of creep."

I do agree with the reviewers though that your manuscript reports some very fine science and the craftsmanship is generally good. I do also think that your manuscript can be reworked to emphasize the novelties more, and highlight how it contributes to us better understanding strain localization in the middle continental crust. By implementing such improvements, I think your paper would become suitable for publication in Solid Earth. In this context, I would invite you to rework the introduction to lead to the formulation of a clear research question or hypothesis.

Response: *We have modified the introduction to clarify the originality of our contribution (see our response above).*

I would also insist that you begin your data presentation with a clear contextualization of your sample(s), that includes SampleID, GPS coordinates and a geo-referenced (outcrop-scale) map that illustrates the structural, mesoscale context.

Response: *We have added in the Section 2 (Geological setting and field description) the requested information: "In this study we analyse a sample of mylonitic shear zone within the Rieserferner granodiorite (sample ID: 10-019A; sample coordinates: N 46°55'24.8" E 12°07'36.2"). The structural, mesoscale context of the studied sample is well illustrated by Ceccato and Pennacchioni (2018) and in particular by their Fig. 4 of their supplementary online material.*

I would then urge you to improve the structure of your discussion so as to clearly address the working hypotheses/research question, discussing your strongest arguments/most significant findings first. As is, the discussion is poorly structured and presents a lot of information in a relatively disengaging way.

Response: *A section header has been added to the Discussion section, to help the reader to follow the structure of the discussion as is.*

As part of this restructuring, I would recommend bringing section 7.3 and the construction of the deformation mechanism maps as the last part of your results section (these are part of your analysis). Section 7.3.1, from p13 line13 onward, should stay in the discussion. This frees up the discussion for placing your findings in the context of established knowledge, including existing knowledge of the shear zones in the Rieserferner pluton.

Response: *The section has been moved to the data section.*

In addition to the above, and the points raised by Referees #1,3 and 4, I would also ask you to consider the following minor comments:

P3, Section 2

Why do you know that the strain gradient you are interpreting is indeed reflecting a progressive evolution (i.e. support the assumption that space is a proxy for time here)?

Response: There is a statement in P3-Section2 where we mention explicitly this point. However, we refer to the recent review paper of Pennacchioni and Mancktelow (2018), and references therein, to interpret that (1) joints provided the structural precursor to shear zones and (2) the fluid-rock interaction at the joint selvages pre-determined the strain gradients of the shear zones. WE believe the above cited paper provides convincing evidence for this mechanism and we "buy" this interpretation as identical structures as those described by Pennacchioni and Mancktelow (2018) have been reported in the Rieserferner pluton in the recent paper by Ceccato and Pennacchioni (2018).

P4, lines 9-17

Not all of these descriptions can be reproduced on the basis of what shown in Fig 1. Either label the figure better or show more appropriate images. All statements here should be supported by images.

Response: In the main text, we have listed all the microstructures recognized in the granodiorite mylonite, but not all are illustrated in the figures. Some of the microstructures are reported in the text for the sake of completeness in the microstructural description, but are not discussed later and are therefore not "relevant" to the main focus of the paper. We therefore prefer to maintain the complete list of microstructures of mylonites without adding additional images to Fig. 1. We will provide high-resolution images so that it will be possible to zoom in and see clearly the microstructural details in the figure.

P4, lines 29-30

Consider that in the final production this figure will be too small to show this properly.

Response: This table is supposed to be published at full-page size. In addition, we will provide high-resolution images so that it will be possible to zoom in and see clearly the microstructural details. We have always taken care of this issue in our published articles.

P5, line 5

No such clusters shown in Fig 3D. Why is the reference to Abart et al relevant here?

Response: Sentence "encircled clusters in Fig. 3d" has been deleted. A similar crystallographic orientation between quartz vermicular grains is better shown in Abart et al. (2014) which is therefore recalled here.

P5, line 8

Where in these figures is this visible? Support with annotations.

Response: An inset showing enlargement of the EBSD map has been added to the figure (Fig. 3e). Low angle boundaries are now indicated by white arrows in Fig. 3e. Figure caption modified accordingly.

P6, line 13

Fig SOM3 has six sub-figures, please be more specific.

Response: OK. In Fig. SOM3b,d,f. The text has been modified accordingly.

P6, line 18

I don't see qtz layers defining a foliation in Fig. 3 and 4 and not SPO inclined to the foliation in Fig. 5.

Response: The quartz layers clearly define the mylonitic foliation in Fig. 2. We admit this was not clear as the figure caption (that has been now corrected) did not reported that the quartz layers were coloured in black; then quartz layers "that generally define the mylonitic foliation" are partially reported in Figs. 4 and 5. The SPO inclination is in effect very weak, but this is not relevant to the topic addressed in the discussion.

P6, line 20-22

This is a weak girdle at maybe 70 degree to XY and even lower angles to the foliation shown in Fig. 5a. The maxima of c and are 30 degrees off X and Y!

Response: The sentence has been modified to: "…Type-II girdle inclined at high angle to the local mylonitic foliation."

P6, line 32

See comment above, pls be specific!

Response: Figure callout modified accordingly.

P7, line 5, also Fig 6

This seems like a small sampling area - how did you ensure it is representative?

Response: The area reported in Fig. 6 is just an example of one of the MANY (to be specific 5 - five) phase maps on which phase distribution analysis has been performed. We have added a sentence in the main text to make this clear: "The results obtained from the analysis of the area shown in Fig. 6 are consistent with the results obtained from other 5 areas (not presented here for the sake of brevity)".

Section 7.2.1 start with a relevant statement (assert), then justify.

Response: OK. We have moved (and modified) the sentence that originally concluded the 1st paragraph as an introductive assertive sentence in the new text: "The microstructures of sheared myrmekite are consistent with GSS creep, including fluid-assisted grain boundary sliding (GBS) (Boullier and Gueguen, 1975; White, 1977; Stünitz and Fitz Gerald, 1993; Fliervoet et al., 1997; Jiang et al., 2000; Wheeler et al., 2001; Lapworth et al., 2002; Bestmann and Prior, 2003; Kilian et al., 2011; Menegon et al., 2013).

P11 line 3

"grain sizes from >40", units missing

Response: μm added.

line 12-13

Given the amounts of sheet silicates obvious in Figure 1, what justifies this step?

Response: Even though the amount of sheet silicates is relevant and it could contribute significantly to the rheology of the real, natural, mylonite; in our calculations we have dealt with a simplified model in which the phases are just quartz and feldspars. In addition, flow laws and parameters for sheet silicates (biotite for example) are not well constrained as those reported for quartz and feldspars. Considering also the contribution of sheet silicates to the rheology of the rock would increase the similarity of the model to the natural case but would also increases exponentially the already existing uncertainties. Please consider the comment of Reviewer #4 that "believes" that complicated models cannot capture the complexity of nature! In contrast, we believe that our model is complicated (or if you prefer simple) enough to provide semi-quantitative information on the rheological behaviour of felsic rocks at mid-crustal conditions (opinion which is shared by Reviewer #2- Elena Miranda, and by Reviewer #3 – James Gilgannon, for example). The fit with field observations of the different extent of strain localization in felsic lithologies (see lines P12-L31 to P13-L12 in previously submitted manuscript) and with experimental data for synthetic poly-phase mixtures (e.g. Xiao et al., 2002) support the relevancy of our model.

P12 line 9

"confining pressure"? Lithostatic pressure?

Response: The term "confining pressure" is adopted by Rybacki et al. (2006) in the description of the flow laws for feldspars. Here we have assumed the "confining pressure" as the lithostatic pressure.

P13 line 2

in my version of the pdf, the brackets contain 4-10-20-100 - what does this mean?

Response: the number were supposed to represent the grain sizes of quartz for which the red curves in Fig. 9b have been calculated. Sentence deleted.

line 3

This statement seems a bit far-fetched. Please elaborate in detail how field observations are supporting your claim.

Response: Our statement is explained by the following sentence in the text inclusive of numerous references. All the reported references well documented that quartz veins under mid-crustal conditions sharply localized ductile shearing within granitoids. Pennacchioni (2005 and, Pennacchioni and Zucchi (2013) also did show that pegmatite layers, though coarser grained, localize strain within granitoid given the weakening effect of myrmekite.

P14 line 3

Please use section headers to preview the section (The effect on what?)

Response: Section header modified accordingly.

line 11

reconsider the use of justify here - this does not seem appropriately used

Response: "justify" changed to "could explain".

P17 lines 10-12

This information should be given in the caption of figure 7.

Response: Sentence moved to caption of Figs. 7 and 8.

P20 line 13

Fix citation of De Toni et al

Response: Done.

Fig 7a - 54 grains - is this really statistically representative? What are the blue curves (I know you mention this in the appendix)? All information necessary to read a figure should be provided in the caption.

Response: see comment above. I know that this amount of data is not statistically representative but this is what we have. In any case, the grain size distribution is similar to the distribution in Fig. 7b, showing the data from a statistically more significant number of grains.

Fig 7c, d - can you please present the data behind these two histograms. In Fig. 4c, you show a value that is less than 1/96th (0.0104, <1.625 um), in 4d two values that are apparently less than 1/86th

(0.0116, <4 um). - Especially, since you cut off the analysis at >=4 um (as you say in A2). Why normalize to 100?

Response: *The cut off value in grain equivalent area is always put at 1 μm². 4 or 9 are the number of PIXELS that, according to the step-size used for EBSD mapping, represent an area of 1 μm². We are sorry but we do not fully understand this comment.*

I look forward to receiving your revised paper.

With kind regards,

Florian Fusseis

Report #1

I reviewed this paper previously, and recommended it to be major revision. In the revised version of the manuscript, main text and figures are modified essentially along with my comments. However, some points in the manuscript as described below should be reconsidered or revised. After sufficient modification, I recommend the revised manuscript will be accepted.

(1) P2, L5–: According to Kretz (1983), abbreviation of plagioclase is Pl, not Plg.

Response: *Reference to Kretz (1983) deleted. The mineral abbreviation is defined when the mineral is first cited in the text.*

(2) P4, L1: Please delete "EM".

Response: *done.*

(3) P5, L5: Where are "encircled clusters" in Fig. 3d.

Response: *This comment had also been raised by the Topical Editor (see our response above). The sentence has been deleted in the new text.*

(4) P8, L10: There is no "section 6.1.2.". It may be "section 7.2.1".

Response: *sentence modified accordingly.*

(5) P11, L28: The unit of the gas constant should be "J K–1 mol–1", "J/K/mol" or "J/(K·mol)".

Response: *corrected to J/K/mol.*

(6) P12, L12–14: At least for me, I cannot find any "details" in supplementary material.

Response: *"Details" refers to the complete description of calculation methods.*

(7) P13, L26–27: Which do you prefer grain size reduction of Qtz resulted from higher strain or higher stress at the margins of the monomineralic layers? If you prefer the former, grain size of Qtz in the layers is not the steady-state one. Is this OK?

Response: Grain size reduction occurred due to an increase in strain toward the margins of monomineralic layers. This could be the result of differential strain rates between microstructural domains (such as monomineralic and polymineralic layers). This is actually a detail, described to explain the variation in grain size that we observe, and that we think is the rule, rather than the exception. Commonly this detail is omitted in the literature. Usually in polymineralic rocks, the recrystallization grain size of pure quartz layers is assumed to reflect the steady-state stress conditions. To avoid misunderstandings, the sentence has been deleted.

(8) P14, L7–8: Please describe the stress condition for "3–4 orders of magnitude increase of strain rate".

Response: Added: "at differential stress conditions of 70 MPa."

(9) P14, L9: Please delete "for a reaction progress factor of □ = 0.25, i.e.", because the sentences related to the reaction progress have been omitted in the revised main text.

Response: deleted.

(10) P14, L30–31: Where do the values of strain rate and differential stress come from?

Response: These values are bracketed by the curves calculated for 10vol% and 20vol% of myrmekite replacement in Fig. 9d. This information has been added in the text.

(11) Fig. 9b: For the model myrmekite, both Pl and Qtz deformed by dislocation creep and by diffusion creep in the dislocation- and the diffusion-creep fields, respectively? If so, grain sizes of Pl and Qtz for the deformation mechanism switch are similar to each other. Perhaps, the mechanism switch of the modeled myrmekite is mainly controlled by that of plagioclase.

Response: Yes, indeed. Probably it is controlled by that.

By the way, the sentence of P11, L19–20 maybe not correct; grain size is not set to be 7 µm in Fig. 9b, but a variable.

Response: Yes, we agree, this is probably a refuse of previous versions. Sentence deleted.

(12) Fig. 9c: For the model myrmekite, grain sizes of Qtz and Pl are set to be 7 µm, and they would not change during deformation. In this case, 7 µm Pl deformed mainly by diffusion creep in the investigated conditions, whereas 7 µm Qtz deformed by diffusion creep at lower differential stresses and by dislocation creep at higher stresses. If so, please describe it in the main text.

Response: This kind of discussion are far beyond the possibilities of the model. In the calculation of myrmekite rheology we are, in some way, averaging the properties of both phases to create a "synthetic" phase with those properties. It is therefore "impossible" to analyse what happens to the individual phases of the aggregate. Our approach is consistent with published flow laws from polymineralic aggregates, which typically derive bulk flow law parameters, rather than parameters for the individual phases (e.g. Dimanov and Dresen, JGR2005).

Report #3

Comments on the manuscript: «Myrmekite and strain weakening in…" by Ceccato, Menegon, Pennacchioni and Morales

This is the second round of reviews after two reviewers have already commented on the manuscript. The comments of the previous reviews have been taken into account during the preparation of this revised version, and the manuscript seems to be more or less ready for publication. Every publication can be improved in one way or another, and the number of different opinions about such changes will depend on the number of reviewers chosen. In order not to extend the review process ad infinitum, I will restrict my comments to some general thoughts and to some aspects, which are incorrect in the present manuscript.

The manuscript documents a strain gradient with parallel reaction progress in a granitoid. The data appears to be of very good quality, and the conclusions are mostly sound and all based on the data presented. I have enjoyed reading the manuscript and I think the material presented is of very good quality.

General aspects:

(1) The P,T-estimates for the myrmekite reaction seem to be very low with 4kb and 420-460C. I am sure that the pseudosection modeling was carried out at the state of the art, and I did not check this in the PhD thesis or other papers. I do not know why the temperatures are so low, but they seem to be too low given some experimental data by Goldsmith, Matthews, and Spear. The problem is the following: The CaAl-silicate (zoisite, epidote) forming reaction is the reaction which separates the stability of albite + CaAl silicate from the stability field of an intermediate plagioclase. For the formation of myrmekite, you need to be on the high temperature side of this reaction, because the Al-conserving feldspar replacement reaction is the reason for the quartz precipitates in the symplectite microstructure. The CaAl-silicate reaction delineates the boundary between greenschist and amphibolite facies, at least in mafic rocks. The only way to stabilize an intermediate plagioclase at low temperatures is at very low pressures, e.g. 3 kb and lower. The 4kb given here seem to be too high for that, so that the lower temperature end of the 420-460C interval certainly is too low, because that definitely is in the greenschist facies. Furthermore, epidote-quartz veins are described in the text, so that greenschist facies conditions clearly are reached.

Response: This comment is too vague. Temperature estimates have been conducted by pseudosection calculations and are reported in the thesis of Ceccato (2018) cited in the text. The thesis is available for evaluation under request. The results of these pseudosection calculations are on their way to be submitted as an article on a scientific journal. In this paper, written in collaboration with Dr. P. Goncalves (Uni. Franche-Comté), we will present the temperature estimates during mylonitization not only in the Rieserferner, but also for other two cases of localized shear zone formation in cooling granitoid plutons (Adamello and Sierra Nevada). In all three cases, pseudosection calculations consistently indicate that mylonitization occurred at temperature in the range between 425°C and 475°C during the pluton cooling. Pseudosection have been calculated using the bulk composition of the mylonites (obtained from XRF), which is very similar in the three cases and is considered representative of the felsic, granitoid, continental middle crust. Therefore, the above discussion about phase equilibria in "[…] at least in mafic rocks", is not applicable. Please note also that formation of myrmekite in deformed rocks has been reported to occur at P-T conditions even lower than those estimated for the Rieserferner (i.e. at 370-400°C, 3-5 kbar, Tsurumi et al., 2003). Thus, we are confident that our P-T estimates are solid and well within the known range of conditions of formation of myrmekite in deformed granitoids.

I think that part of the problem is that the shear zones described here have a fairly extended temperature history. In figure 2, there is a well-documented strain and reaction evolution in the protomylonite and mylonite with increasing amounts of myrmekite. The ultramylonite is described as a mixture of plagioclase, epidote, biotite, etc. So, for me this looks like a first stage of the deformation history, in which the protomylonite and mylonite have formed (in the amphibolite facies, and with the myrmekite reaction), and, subsequently, the ultramylonite with a greenschist facies assemblage has formed. If biotite continues to change its composition in the amphibolite facies part of the shear zone during later lower P,T conditions, the temperature estimates may be rather low as a consequence of that, but I can only speculate on the reasons for the low temperature estimate.

The temperature estimate is critical for the rheology calculations, of course. It would be a good idea to make it clear that the temperature estimates chosen for the rheological modeling are at the minimum limit for these shear zones.

Response: We disagree with this speculative interpretation. The microstructural and petrographic evolution of these rocks (Adamello and Rieserferner) has been described thoroughly in the paper of Bestmann et al., 2015 and in the PhD thesis of Ceccato (2018).

(2) The rheological model seems to follow an approach by Dimanov and Dresen (2005) and Platt (2015). As Dimanov and Dresen express it so well in their paper: "At this point it seems impossible to suggest a suitable continuum model that captures the material behavior … offering more than a purely phenomenological or qualitative description." And they have tried to model only two phases for which they have had good experimental data. The attempt made here is a very complex model with lots of different parameters, deformation mechanisms, combinations of materials, etc. I personally think that by making models more complicated we do not learn more or come closer to explaining what happens in nature. But that is my personal opinion, and as the model in this manuscript follows some approach already presented in the literature, it is up to the authors what they want to publish.

Response: Yes, the model is quite complicated, with lot of different parameters and flow laws, as models often are. The paragraph of the Dimanov and Dresen's paper continues as follow: "Existing models, however, may give some guidance as to how constitutive parameters and strength of pure end-member phases vary for small volume fractions of weak or strong inclusions dispersed in a strong or weak matrix, respectively". This is the aim of this paper, trying to quantify at least in terms of order of magnitude, the relative strength of polyphase vs. monophase aggregates.

The results of rheological calculations presented here are then validated by comparison with both experimental data and natural examples of competence contrasts during viscous deformation of the felsic middle crust.

For example, the den Brok model for quartz is making rather special assumptions about island and channel structures and he makes it clear that his model produces much faster strain rates than conventional diffusion creep models. But Platt (2015) chooses this model as something that is available, without giving good reasons for using it. It would perhaps have been more instructive to present a simpler model here with only end-member rheologies.

Response: We do not understand which end-member rheologies should be more appropriate here. Using end-member rheologies would be rather a simple "exercise of style" and it would not show any novelty. In addition, the authors are well aware of the different models described in den Brok

(1998), as also Platt (2015) was. Here we use the flow law parameters described for the thin-film model. Not the island-and-channel model.

*From den Brok (1998) paper: "It appears that the PS rate predicted for the **<u>thin-film model</u>** may be more than ten orders of magnitude <u>**lower than**</u> PS rate for <u>**the island-channel model**</u>. The reason for this discrepancy is that at T = 200 °C, the predicted effective grain-boundary diffusivity (Dw) for the thin-film model, where material diffuses through a very thin and structured water film, is ~10–29 m3/s (Farver and Yund, 1991), which is more than ten orders of magnitude lower than the effective diffusivity predicted for the island-channel model, where material diffuses through relatively wide channels filled with water having the properties of a bulk fluid (Dw = 5 × 10–17 m3/s, for D = 10–9 m2/s and w = 50 nm). <u>**Note, that at T = 400 •C the predicted PS strain rate for the island-channel is about 7 orders of magnitude higher than for the thin-film model**</u>."*

Another aspect of the rheological discussion may be that it should be more clearly stated that the model more or less assumes something close to a Reuss lower bound, because it is assumed that the weak layers are connected. It is not clear that this assumption is also made for the granitoid case, for example.

Response: *Yes, this is stated clearly in the Dimanov and Dresen (2005) paper, from which the applied model is developed. Added sentence in the text (Section 7.3).*

Detailed comments:

p.2, line 6-9: Myrmekite formation is ALWAYS the result of a chemical metastability of K-feldspar, not of a stress concentration. The location, where the reaction takes place, may be controlled by the stress field (among other factors).

Response*: together with myrmekite formation and Kfs dismantling at high stress sites, there is also the concomitant deposition of K-feldspar at dilatant grain boundaries and around porphyroclasts in stress and strain shadows (e.g. Fig. 4a, Area D or sparse Kfs grains in the matrix of Fig.3). The concomitant precipitation of K-feldspar neoblasts in dilatant sites is consistently documented in all the studies dealing with myrmekite formation in deformed granitoids, from the inspiring work of Simpson and Wintsch (1989) onwards. This is at the core of the work on myrmekite in the last decades, and has led to the consistent conclusion that stress concentrations and strain energy are the main drivers for the myrmekite reaction in deformed rocks. The review by Vernon (1991) has highlighted these aspects very well. A metastable mineral phase is not supposed to precipitate or grow. Therefore, Kfs was a stable mineral phase during deformation of Rieserferner mylonites.*

Figure 6: The surface fraction of quartz boundaries is a wrong label on the x-axis, or the data is plotted incorrectly. The quartz surface area fraction should not be 55-60%, if quartz makes up only 18 vol% of the mixture, as described in the text. The points should be plotted mirror-symmetrically on the other side of the vertical 50% line. It then also is more consistent in that the feldspar grain boundaries plot close to their expected frequency.

Response: *Yes, we agree that if the data are plotted mirror-symmetrically they would plot closer to the theoretical probability curves. We would have appreciated, in a constructive review, a suggestion on to why the points "should be plotted" in one or the other way.*

The discrepancy between area fraction of quartz (vol%) and the surface fraction of quartz boundaries reported here is probably due to the different grain sizes and shapes between quartz and plagioclase in the analysed aggregates. In fact, area fraction equals the surface fraction of boundaries only in the case in which both phases show the same grain size and shape (Heilbronner and Barrett, 2014; Sections 18.1.2-18.1.3; pp. 355-356). According to the difference in grain size or shape, the volume or surface fraction should be adopted as x-axis in the probability plot (see Section 18.4.1, pp 361-363 in Heilbronner and Barrett, 2014).

Here we have adopted the surface fraction of boundaries as x-axis, given that the grain size is the parameter that is readily quantifiable and shows a significant difference between quartz and plagioclase. The surface fraction of quartz boundaries was calculated as the ratio between the sum of the length of quartz grain boundaries and quartz-plagioclase phase boundaries, and the sum of the length of ALL grain (quartz and plagioclase) and phase boundaries. We have checked all the calculations and the results of our image analysis on all the five phase maps, and we confirm that the plots are correct. The phase maps are available to the interested readers who would like to use them.

p.8, line 28: Why does the quartz coarsening imply grain size reduction in plagioclase? They could both grow.

Response: Honestly, we have no idea. This is simply what we observed in the microstructure, but cannot provide a clear explanation.

p.10, line 21: please omit "strong". There is a CPO, but not a strong one.

Response: done.

Figure 9: the largest quartz grain size in Figure 9a is plotted as 30 microns, but the measured grain size distribution gives modes of 20 for the small and 70 microns for the large fraction (Figure 7d). I did not understand why, but I might have missed something here.

Response: 35 μm is the divide between "small" and "large" grain sizes.

p.14, line 16-20: this inference cannot really be made, because the myrmekite reaction is a chemical reaction, and its progress is not dependent on rheology. It is correct that the strain and the reaction progress are connected here, but it is not possible to argue for more progress of the reaction based on a weakening of the rock. In other words, the reaction correlates with strain, but it does not necessarily depend on strain rate.

Response: This was not the meaning of our statements and we agree that the reaction progress does not correlate with strain rate. We intended to say that it correlates with strain and with the progressive grain size reduction of the host rock. We have modified the text to be clearer.

p.15, line 20: The phase mixing does not impede dynamic recrystallization – the grain size sensitive processes are more efficient in terms of rheology, that is all.

Response: *We agree, the term "dynamic recrystallization" is probably misleading in this context. Dynamic recrystallization, in general is related to dislocation creep mechanisms. Dislocation creep is superseded by diffusion creep when the grain size is maintained very fine as a consequence of second-phase-pinning.*

Reviewer #4, James Gilgannon.

Dear Editor,

At your request I have reviewed the rheological aspects of the discussion in the contribution of Ceccato et al. (2018), titled 'Myrmekite and strain weakening in granitoid mylonites'. Ceccato et al. provide a robust observational basis from which to explore the rheology of a granitoid rock that has undergone microstructural change by myrmekite formation. The authors use a combination of analytical and empirical rheological equations to make statements about the changes in strength of their samples and strain partitioning during creep.

Specifically, Ceccato et al. compare:

(1) a hypothetical granitoid rheology (which is grain size insensitive (GSI) and analytically derived);

(2) the rheology of pure quartz layers (for both grain size sensitive (GSS) and GSI creep);

(3) and the rheology of sheared myrmekite, which is calculated from microstructural observations

of grain size and phase proportions (again for both GSS and GSI creep).

The authors find that the rheological analysis supports the assumption that the myrmekite, produced sny-kinematically, is weaker than the rest of the mylonite's constitutive parts. The interpreted weakness is then postulated to promote strain partitioning in the mylonite.

General comments:

With the inclusion of the rheological discussion the authors provide the contribution with a rounded perspective. Specifically they advance our understanding by applying the results of laboratory and theoretical works to a natural example. This links the microstructural analysis to the current understanding of the physics of creep. I particularly like the inclusion of the experimental results of Xiao et al. (2002) for comparison. This anchors the analytical rheological equation used for the sheared myrmekite to a comparable phenomenological work. It is also of note that the protolith used for comparison is not assumed to be a mono-mineralic flow law but that the authors construct a poly-mineralic law for a granitoid. I think this makes for a much better comparison and brings us closer towards the complexity of nature. The work is considered and well written and I recommend it for publication.

That being said, I have a few minor comments that may make the work clearer at points for those not expert in rheology.

Best,

James Gilgannon

Specific comments for the Authors:

TEXT

P11, L29:

The contribution of pressure-solution creep in Qtz has been calculated following the flow law for thin-film pressure-solution of den Brok (1998): Previously it is written that you consider diffusion creep of quartz (P11, L17) and here you talk of pressure solution with no intermediate step in explanation. As there are many diffusion creep models that all have very similar forms it is probably helpful for the reader to have a step from the statement in line L17 to L29. Therefore I would be inclined to reformulate the sentence to something like:

'The contribution of diffusion creep in quartz is considered to come from pressure-solution creep and has been calculated using the flow law for thin-film pressure-solution of den Brok (1998):'

Response: *we have reformulated the sentence as suggested.*

P12, L6-14:

For feldspar, the flow laws of Rybacki et al. (2006) […] Details on the derivation of the deformation mechanism maps and on the calculation of the flow laws are given in the online supplementary material. I think here you might want to invert the order: introduce the approach used for defining the polymineralic aggregates and then cite the feldspar laws. Something to the effect of: 'The flow laws for poly-mineralic aggregates (e.g. sheared myrmekite and mica-free granitoid) have been calculated following the approach of Dimanov and Dresen (2005) and Platt (2015). The method allows a poly-mineralic aggregate flow law to be constructed by considering the proportional contribution of the minerals in the aggregate. The resulting flow laws for the polymineralic aggregates can be derived for both a GSS and GSI rheology and are outlined in detail in the supplementary material. In our calculations only quartz and feldspar are considered as minerals of the aggregates. For quartz the flow laws used are those above (eq. 1 and 2), while for feldspar, the flow laws of Rybacki et al. (2006) have been used to calculate the contribution of dislocation and diffusion creep:

EQUATION 3

where: A_f is the pre-exponential factor for feldspar (MPa-n μmm s-1); d is the grain size (μm); m is the grain-size exponent (m=3 for diffusion creep; m=0 for dislocation creep); p is the confining pressure (MPa); V_{act} is the activation volume (m3 mol-1). Flow law parameters are listed in Table 1. Details on the derivation of the deformation mechanism maps and on the calculation of the flow laws are given in the online supplementary material.'This is just a rough rearrangement of what you wrote but with an additional couple of statements. I think this makes the flow of this section easier. Otherwise you introduce feldspar as a rheology after you state you will only consider quartz and poly-mineralic aggregates and not pure feldspar. In this order it makes it clearer that feldspar is used as a part of the poly-mineralic calculation.

Response: *We agree and the paragraph was modified accordingly.*

P14, L9:

observed for a reaction progress factor…

Prior to this there is no mention of the reaction progress factor. I am unsure where this fits in the analysis. In the supplementary material I could access I did not see any mention of this factor. From reading the previously submitted draft, I think since your revisions you have moved the mention of

this parameter to the supplementary material. I would recommend that you point to where it can be found in the supplementary material.

Response: *sentence deleted.*

EQUATIONS

I would recommend that the strain rates for each mechanism be uniquely labelled with sub/superscripts. The reason for this is that in your rheological calculations the total strain rate is assumed to be equal to the sum of a set of strain rates from those unique mechanisms. Unique labels help make this clearer. For equation 3 that might involve breaking it into two equations: one for dislocation creep and one for diffusion creep.

Response: *Text modified accordingly.*

FIGURE CAPTIONS

Figure caption 9:

I think that the caption for figure 9b needs some smoothing out.

P28, L6:

(b) A and B marked red polygons represent the differential stress range derived from piezometric calculations on pure Qtz layers (red and black stars along respective piezometric curves). I think that you are referring to what you take as the iso-stress values for the red polygon in fig. 9b but it is not clear because A and B are not present in figure 9b.

Response: sentence deleted.

FIGURES

Figure 2:

On the version I have there is no scale, however the inclusion of a scale might help the reader.

Response: scale included.

Figure 9:

Fig 9b)

You have a lot of information in this figure. Currently, I think that the 'black box' is hard to identify because there is also the grey polygon and all of the log-log lines. If you don't wish to break up the figure, you might consider labelling the vertical lines with the corresponding grain sizes or making the 'black box' something else, like a hatched box and making the log-log lines considerably more transparent.

Response: black rectangle thickened.

Fig 9c)

Here you plot pure feldspar for An100 and An60 but do not discuss it in the text. I would remove these from the plot. In your discussion you focus on comparing pure quartz, the sheared myrmekite and the mica-free granitoid and do not discuss the role of pure feldspar.

Response: We prefer to keep the rheological curves for the different compositions of plagioclase as a useful comparison with experimental data.

Myrmekite and strain weakening in granitoid mylonites

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Abstract. At mid-crustal conditions, deformation of feldspar is mainly accommodated by a combination of fracturing, dissolution/precipitation and reaction-weakening mechanisms. In particular, K-feldspar is reaction-weakened by formation of strain-induced myrmekite - a fine-grained symplectite of plagioclase and quartz. Here we use EBSD (i) to investigate the microstructure of a granodiorite mylonite, developed at ~ 450 °C during cooling of the Rieserferner pluton (Eastern Alps), and (ii) to assess the microstructural processes and the weakening associated with myrmekite development. Our analysis shows that the crystallographic orientation of plagioclase in pristine myrmekite was controlled by that of the replaced K-feldspar. Myrmekite nucleation resulted in both grain size reduction and anticlustered phase mixing by heterogeneous nucleation of quartz and plagioclase. The fine grain size of sheared myrmekite promoted grain size-sensitive creep mechanisms including fluid-assisted grain boundary sliding in plagioclase, coupled with heterogeneous nucleation of quartz within creep cavitation pores. Flow laws, calculated for monomineralic quartz, feldspar, and quartz + plagioclase aggregates (sheared myrmekite) during deformation at 450 °C, show that grain-size-sensitive creep in sheared myrmekite accommodated strain rates several orders of magnitude higher than monomineralic quartz layers deforming by dislocation creep. Therefore, diffusion creep and grain size-sensitive processes contributed significantly to bulk rock weakening during mylonitization. Our results have implications for modelling the rheology of the felsic middle crust.

1. Introduction

Localization of ductile strain within rocks arises from weakening associated with grain size refinement processes by dynamic recrystallization, metamorphic reactions, and microfracturing (e.g. Platt et al., 2015, and reference therein). Grain size reduction, accompanied by phase mixing in polymineralic rocks at high strains, commonly results in a switch of deformation mechanism from grain-size-insensitive (GSI) to grain-size-sensitive (GSS) creep – one of the most effective strain weakening mechanisms within shear zones (Kruse and Stünitz, 1999; Kilian et al., 2011; Menegon et al., 2013).

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Feldspars locally form the load-bearing framework of crustal rocks (Handy, 1994). At mid-crustal conditions, feldspar deformation mainly occurs by microfracturing and dissolution/precipitation processes, typically associated with metamorphic reactions (Behrmann and Mainprice, 1987; Michibayashi, 1996; Stünitz and Tullis, 2001; Gueydan et al., 2003; Ree al., 2005). Kfs (K-feldspar — mineral abbreviations in the text are according to Kretz, 1983) is commonly replaced by myrmekite – a fine-grained symplectic aggregate of Qtz (quartz) and Plg (plagioclase) (Becke, 1908; Vernon, 1991). Myrmekite replacement is either related to Kfs chemical instability (Cesare et al., 2002), in some cases involving local metasomatic fluids (Phillips, 1980), or triggered by stress concentration and intracrystalline strain in Kfs during deformation (Simpson and Wintsch, 1989; Menegon et al., 2006). This replacement is acknowledged as a weakening mechanism during ductile deformation of granitoid rocks (LaTour and Barnett, 1987; Simpson and Wintsch, 1989; MacCaffrey, 1994; O'Hara et al., 1997; Tsurumi et al., 2003; Pennacchioni, 2005; Menegon et al., 2006; Pennacchioni and Zucchi, 2013; De Toni et al., 2016). Deformation and shearing of myrmekite result in a fine-grained Plg + Qtz aggregate, that is manifestly weaker than original coarse Kfs (Tsurumi et al. 2003; Ree et al., 2005; Ciancaleoni and Marquer, 2006). In general, a fine grain size and the local presence of grain boundary aqueous fluid promote phase mixing and the development of ultramylonites (Vernon, 1991; Kilian et al., 2011; Czaplińska et al., 2015). Though the key role of myrmekite in strain localization has been recognized, it has not been accompanied with a quantitative analysis of the deformation mechanisms within myrmekite-derived, fine-grained Plg + Qtz aggregates.

Here we present a detailed analysis of myrmekite evolution, from the nucleation stage within Kfs to the development of sheared Plg + Qtz aggregates, and of the associated rheological weakening that resulted in strain localization in the mylonites of the Rieserferner granitoid pluton (Eastern Alps). In this pluton, ductile shear zones nucleated along joints that were locally filled with Qtz and Ep (epidote) veins during post-magmatic cooling (Ceccato et al., 2017; Ceccato and Pennacchioni, 2018). The progressive development of granodiorite mylonite was associated with consumption of Kfs by myrmekite leading to increasingly interconnected, fine-grained Plg + Qtz layers. Microstructures of granodiorite mylonite have been analysed to characterize: (i) the process of myrmekite nucleation; (ii) the deformation mechanisms during myrmekite shearing and transition to Plg + Qtz aggregates; (iii) the deformation mechanisms of pure Qtz layers; (v) the deformation mechanisms of Kfs porphyroclasts and of Kfs new grains during mylonitization. Furthermore, the application of mixed flow laws of the aforementioned deformation mechanisms for polymineralic aggregates allows the degree of rheological weakening resulting from deformation of myrmekite to be quantified. The current paper represents a first attempt at quantitatively estimating, based on a robust microstructural analysis, the

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rheological effects of the development of myrmekite during mylonitization of granitoids, and at determining the deformation mechanisms in syn-kinematic monomineralic and polymineralic aggregates at mid-crustal conditions. This estimate was not attempted yet (e.g. LaTour and Barnett, 1987; Simpson and Wintsch, 1989; MacCaffrey, 1994; O'Hara et al., 1997; Tsurumi et al., 2003; Pennacchioni, 2005; Menegon et al., 2006; Pennacchioni and Zucchi, 2013; De Toni et al., 2016). A validation to This analysis is validated by comparison with experimental data on deformation of poly-phase mixtures. This analysis is validated by……

Therefore, this paper aims to represent the first case study in which the deformation mechanisms are quantitatively analysed by up to dated analytical techniques (EBSD, CL) and strain localization description is accompanied by a quantitative evaluation of the stress and strain conditions. The results of rheological calculations about lithologically-controlled rheology presented here are compared to, and their validity supported by, experimental data and natural examples of compositionally-dependent ductile strain localization.

2. Geological setting and field description

The tonalitic-granodioritic Rieserferner pluton (Eastern Alps) (Bellieni, 1978) was emplaced at ~15 km depth (0.4 GPa; Cesare et al., 2010) into the Austroalpine nappe system at 32 Ma (Romer and Siegesmund, 2003). During post-magmatic cooling, a main set of ductile shear zones exploited shallowly ESE-dipping joints, and the joint-filling Qtz and Ep veins (set 2 of Ceccato, 2018; Ceccato and Pennacchioni, 2018). The temperature of ductile shearing has been estimated at 420-460 °C based on thermodynamic modelling (Ceccato, 2018). Ductile shearing along joints and Ep-filled joints resulted in cm-thick heterogeneous shear zones with a sigmoidal-shaped foliation in the host granodiorite (Ceccato and Pennacchioni, 2018) likely reflecting fluid-rock interaction at the vein selvages (Pennacchioni and Mancktelow, 2018). In contrast, Qtz veins filling the joints sharply localized homogeneous shearing (Ceccato et al., 2017).

The In this study we analyse a sample of mylonitic shear zone within the Rieserferner granodiorite (sample ID: 10-019A; sample coordinates: N 46°55'24.8" E 12°07'36.2"). of heterogeneous shear zone analysed here (10-019A) comes from the outcrops just north of the glacial lake at the base of the Hochgall Ferner, in the Rieserferner Group (GPS coordinates: N 46°55'24.8" E 12°07'36.2"); The structural, mesoscale

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The mesostructural context of the studied sample is well seillustrated by structures are widely described and discussed in Ceccato and Pennacchioni (2018) and in particular by their map ofin Fig. 4 of their (supplementary online material). This set of ESE dipping shear zones with top to ESE normal kinematics probably represent the mid crustal ductile roots of a low angle normal faults system.

The sample of heterogeneous shear zone analysed here (10-019A) comes from the outcrops just north of the glacial lake at the base of the Hochgall Ferner, in the Rieserferner Group (GPS coordinates: N 46°55'24.8" E 12°07'36.2").

3. Analytical methods

Polished thin sections of granodiorite mylonite were prepared for the study of the microstructure and of the crystallographic preferred orientations (CPO). The thin sections were made from rock chips cut parallel to the stretching lineation and perpendicular to the shear plane (XZ plane of finite strain ellipsoid).

Electron backscattered diffraction analysis was carried out on a JEOL 7001 FEG SEM equipped with a NordLys Max EBSD detector (AZTec acquisition software, Oxford Instruments) at the Electron Microscopy Centre of Plymouth University. EBSD patterns were acquired on rectangular grids with step sizes of 0.2, 0.3 and 0.35 μm. Working conditions during acquisition of EBSD patterns were 20 kV, 70° sample tilt, high vacuum, and working distance between 17 and 23 mm. A detailed description of the EBSD post-processing methods and of the image analysis are reported in Appendix A. The microstructural and CPO analysis conducted with EBSD were complemented with cathodoluminescence (CL) and microchemical analyses.

CL imaging was performed in a FEI Quanta 200 FEI equipped with Gatan monocle detector. Imaging was performed using an accelerating voltage of 20 kV, beam current of 8 nA and working distance of 20 mm in C-coated (15 nm) thin sections used for EBSD analysis. To avoid incorrect interpretation of potential artefacts in the sample, secondary (SE) and backscatter electron images were collected simultaneously with CL.

Microchemical analyses were performed with EM wavelength-dispersive spectroscopy (WDS) at Electron Microprobe Laboratory at the Università degli Studi di Milano with a Jeol 8200 Super Probe; the operating conditions were: 15 kV accelerating voltage; 5 nA (Kfs and Plg) beam current. PAP correction program was applied to convert X-ray counts into oxide weight percentages.

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4. Microstructure

The Rieserferner granodiorite consists of Qtz, Plg, Kfs, Bt (biotite), Ep, Hbl (hornblende), Ap (apatite), and Ttn (titanite). The magmatic Plg displays normal oscillatory zoning ($An_{58} - An_{32}$). Plg crystals are arranged in glomeroclasts, included in Kfs ($Or_{93}Ab_7$). Various grain-size reduction mechanisms accompanied the development of a mylonitic foliation in the granodiorite: (i) recrystallization of Qtz and Bt (Fig. 1a,b); (ii) formation of myrmekite after Kfs (Fig. 1c,d); (iii) microfracturing of feldspar; and (iv) formation of Plg ($An_{29}Ab_{71}Or_{<1}$) + Ttn + Wmca (White Mica) symplectite at Bt-Plg boundaries (Pennacchioni et al., 2006; Johnson et al., 2008). Pristine myrmekite make a transition to fine grained aggregates of dominant Plg + Qtz extending into the foliation (Fig. 1b,e). The mylonitic foliation is defined by alternating layers of: (i) monomineralic Qtz; (ii) Plg ($An_{26}Ab_{74}Or_{<1}$) + Qtz + Kfs; and (iii) Bt and recrystallized Bt/Plg (Fig. 1a). Syn-kinematic Kfs neoblasts ($Or_{96}Ab_4$) are found in strain shadows around porphyroclasts and dilatant fractures, and are in turn locally replaced by myrmekite (Fig. 1d).

With increasing strain, the volume percentage of Kfs decreases from 19 vol% (undeformed rock and protomylonite), to 1-6 vol% (rare scattered porphyroclasts in mylonite and ultramylonite) (Fig. 2). As counterbalance, the volume percentage of fine-grained myrmekite and derived Plg + Qtz aggregates, increases from 3 vol% (undeformed rock and protomylonite) to as much as 13 vol% (mylonite and ultramylonite) (Fig. 2). Ultramylonites consist of a fine-grained (ca. 10 µm grain size) well-mixed matrix of Qtz, Plg, Bt, Ep, Kfs, Ttn, Ap ± Grt (Garnet) ± Wmca.

5. EBSD and cathodoluminescence analysis

5.1 Pristine myrmekite

Pristine myrmekite shows: (i) preferential development along grain boundaries of Kfs porphyroclast oriented parallel to the mylonitic foliation (Fig. 1b-e); (ii) lobate shape protruding into the Kfs (Fig. 1c); (iii) single grain structure of Plg within each lobe, embedding vermicular Qtz; (iv) rather constant spacing of Qtz vermicules of about 3-5 µm across the entire lobe (Fig. 1g); and (v) preferential elongation of the Qtz vermicules orthogonal to the myrmekite/Kfs boundary (Fig. 1g).

The EBSD analysis shows that: (i) Kfs and myrmekitic Plg commonly have similar crystallographic orientations (($100)_{Kfs}$ || $(100)_{Plg}$, $(010)_{Kfs}$ || $(010)_{Plg}$, and $(001)_{Kfs}$ || $(001)_{Plg}$: Fig. 3b, c); (ii) Qtz vermicules do not share any crystallographic plane or direction with Kfs or myrmekitic Plg (Fig. 3b-c-d); (iii) Qtz vermicules do not show any obvious CPO, but they usually have similar crystallographic

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orientation within a myrmekite lobe (see encircled clusters in Fig. 3d) (similar to what reported by Abart et al., 2014); and (iv) Dauphiné and Albite twins are occasionally observed in Qtz and Plg, respectively.

The Plg of myrmekite lobes exhibits rare low angle boundaries (misorientations >2°, >5°) that abut against the Qtz vermicules (Figs. 3a 3cand 4a). The internal distortion of myrmekitic Plg is very small (<1°; Fig. SOM1a).

5.2 Sheared myrmekite: plagioclase + quartz aggregates

Plg + Qtz aggregates (± rare Kfs and Bt) wrap around Kfs porphyroclasts and are elongate into the foliation (Fig. 1e). These aggregates make transition to, and extend into the foliation from, pristine myrmekite and are hereafter referred to as sheared myrmekite.

Qtz grains in sheared myrmekite occur either as isolated single grains at triple/quadruple junctions between Plg grains or, less commonly, as polycrystalline aggregates elongated normal to the foliation (Fig. 4a). Qtz grains within sheared myrmekite have no CPO (Fig. 4b), show little internal distortion and show rare low angle boundaries with scattered misorientation axis distribution (Fig. 4c). Misorientation angle distribution for correlated pairs displays higher frequency than a random-pair distribution for misorientations < 15° and at 60° (Fig. 4d). The uncorrelated misorientation angle distribution approaches the random-pair distribution.

Plg grains do not show any obvious CPO (Fig. 4e), and display little internal distortion and rare low angle boundaries. The low and high angle misorientation axes in crystal coordinate system are almost uniformly distributed (Fig. 4f). Even though very close to random-pair distribution, correlated misorientation distribution exhibits two distinct peaks at very low angles (<5-10°) and close to 180° (Fig. 4g). Misorientations <70° occurs with slightly higher frequency than the random-pair distribution. Albite-twins and related 180° misorientations are rarely observed inside new grains (Figs. 3a-4a). In CL both myrmekitic Plg and Qtz have a grey shade similar to the surrounding non-myrmekitic Plg and Qtz (similar to Hopson and Ramseyer, 1990) (Fig. 1f,h).

5.3 K-feldspar aggregates in strain shadows

In this section, EBSD data are used to describe the relationship between Kfs neoblasts and porphyroclasts. Kfs neoblasts occur in strain shadows around feldspar porphyroclasts, as well as dispersed within the sheared myrmekite (Figs. 3a, Area C in Fig. 4a; Fig. SOM2). In strain shadows, the orientation of (100), (010) planes and [001] direction of the neoblasts is similar to that of the

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porphyroclast (Fig. 4h-j). In particular, the Kfs neoblasts show a CPO for (010) planes close to the Y kinematic axis (Fig. SOM2d), which is similar to the orientation of (010) in the adjacent porphyroclast. Misorientation axis/angle distributions show very few scattered data without any clear clustering (Fig. 4k). The grain size of new Kfs grains dispersed within sheared myrmekite is ca. 7 µm, comparable to

5 that of the Plg in the surrounding sheared myrmekite (Fig. 5l).

The CL imaging of Kfs highlights a complex microstructure, which is different between new grains and porphyroclasts. The porphyroclasts show a homogeneous bright shade overprinted by a complex pattern of low-grey CL shade (seeindicated by whiteblack arrows in Fig. SOM3b,d,f). Kfs grains in sheared myrmekite and tails around porphyroclasts show a homogeneous low-grey CL shade

10 (indicated by black arrows in Fig. 1f-hSOM3). Kfs aggregates elongated parallel to the foliation and enveloped by sheared myrmekite are characterized by bright irregularly-shaped Kfs cores (porphyroclasts) surrounded by low-grey shaded Kfs.

5.4 Quartz layers along foliation

Monomineralic Qtz layers defining the mylonitic foliation (Figs. 2, 3, 4 and 5) show a variable grain

15 size, and a shape preferred orientation (SPO) weakly inclined to the foliation consistently with the sense of shear. Dauphiné twin boundaries are widespread (red boundaries in Fig. 5a). The Qtz c-axis CPO defines an asymmetric Type-II girdle roughly normalinclined at high angle to the local mylonitic foliation (Fig. 5b). The pole figures of c-axis and <a> directions show maxima roughly aligned withclose to the Y and to the X kinematic directions, respectively. Misorientation axis distribution for

20 low angle misorientation (<10°) exhibits a wide maximum close to c-axis and $<\pi-\pi'>$ directions in crystal coordinates. These misorientation axes preferentially cluster close to (but slightly off-set from) the Y-kinematic direction in sample coordinates (Fig. 5c). High angle misorientation axis distributions do not show any clear systematic pattern, except for misorientations around 60°. Misorientation angle distribution (Fig. 5d) shows two peaks at very low angle misorientations (<10°) and around 60° for

25 correlated misorientations. Un-correlated misorientation angle distribution is close to the random-pair distribution. CPOs and misorientation data of coarser grains do not differ from those of finer grains. In CL images the Qtz layers display an overall homogeneous signature, with lower-grey shades close to inclusions and layer boundaries (central quartz layers in Fig. SOM3b).

6. Phase spatial distribution, grain size and aspect ratio

30 The results of image analysis of EBSD phase maps indicate that pristine and sheared myrmekite have the same phase ratio with ca. 18 vol% of Qtz. We have analysed the phase spatial distribution of Plg

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and Qtz in both pristine and sheared myrmekite to define their deviation from a random distribution, either towards a clustered or an anticlustered distribution (Heilbronner and Barrett, 2014). Phase spatial distribution analysis of a two-phase aggregate compares the cumulative lengths of phase boundaries (boundaries between grains of a different phase) and of grain boundaries (boundaries between grains

5 of the same phase) with those expected for a random distribution of the two phases. We have considered three types of boundaries: (i) Plg – Plg grain boundaries; (ii) Qtz – Qtz grain boundaries; and (iii) Plg – Qtz phase boundaries. The results (Fig. 6) show that, in pristine and sheared myrmekite: (i) the surface area fraction of Qtz ranges between 0.55-0.75 and 0.55-0.65, respectively; (ii) Qtz – Qtz grain boundaries occur with a lower probability than for a random distribution, indicative of an

10 anticlustered distribution; (iii) Plg – Plg grain boundaries occur with a higher probability than for a random distribution indicative of a more clustered distribution; and (iv) Plg + Qtz aggregates display an anticlustered distribution, with Plg – Qtz phase boundaries occurring with higher probability than for random distribution of phases. The results obtained from the analysis of the area shown in Fig. 6 are consistent with the results obtained from other 5 areas (not presented here for the sake of brevity).

15 Grain size distributions for Qtz (Fig. 7) and Plg (Fig. 8) are quite different for pristine myrmekite, sheared myrmekite and in monomineralic Qtz layers. In pristine myrmekite, large single grains of Plg (20-50 µm, Fig. 8a) embed Qtz vermicules ~3 µm in equivalent diameter (Fig. 7a). In sheared myrmekite, Qtz grain size is around 3 µm (Area B in Fig. 4a; Fig. 7b), but locally increases to >10 µm (Area C in Fig. 4a; Fig. 7c); individual Qtz grains show polygonal, equant shapes (aspect ratio AR,

20 ratio of long to short axis; 1.5<AR<1.75; Fig. 7e) or a weak shape preferred orientation (SPO) oriented at low angle to the local mylonitic foliation (Fig. 7e). Plg grains (average grain size of about 7 µm: Figs. 8b-c) are mainly polygonal and range in shape from almost equant to elongated (1.75<AR<2; Fig. 8d). Elongated grains define an SPO almost parallel to the local mylonitic foliation (Fig.8d for Area B in Fig. 4a).

25 Monomineralic Qtz layers along the foliation show a variable grain size, usually ranging between 10 µm and 120 µm, mimicking a bimodal grain size distribution with maxima centred respectively at 20-35 µm and 50-70 µm (Figs. 7d and SOM4). The coarser grain size (>40 µm) is observed close to the centre of Qtz layers. These grains are usually characterized by subgrains ranging in size between 20 and 35 µm. The smaller grain size (<40 µm) commonly envelopes the coarser grains, in addition to

30 prevail at the boundary between monomineralic Qtz layers and sheared myrmekite, or around feldspar porphyroclasts (Figs. 3, 4 and SOM4e).

7. The rheology of the Rieserferner mylonites

The rheological effect of transformation of coarse Kfs to fine-grained sheared myrmekite and the transition to an interconnected, weak, fine-grained microstructure (Handy, 1990) is estimated here by investigating the deformational behaviour of different mixtures of Plg and Qtz, in which deformation is accommodated either by dislocation creep or by diffusion creep. Our simplified model does not include Bt, Wmca and Bt + Plg aggregates. Based on the deformation mechanisms identified from the microstructural analysis, deformation mechanisms maps have been calculated and plotted on grain-size vs. differential stress and on differential-stress vs. strain rate diagrams for the following three end-member compositions (Fig. 9):

(i)   monomineralic Qtz layer deforming via both dislocation and diffusion creep (Fig. 9a);

(ii)   sheared myrmekite, modelled as 80 vol% Plg (An_{60}) + 20 vol% Qtz deforming via both dislocation creep and grain size sensitive creep (Fig. 9b); the input grain size is 7 μm, identical for both minerals;

(iii)   a mixture of 60% Plg (An_{100}) + 40% Qtz assumed as a simplified composition representative of a mica-free granitoid rock deforming only by dislocation creep (after referred as "granitoid") (Fig.9c).

The flow law of Hirth et al. (2001) has been used to calculate the dislocation creep component in deformation mechanisms maps for Qtz:

(1) $\dot{\varepsilon} = A_q f_h \sigma^n e^{(-\frac{Q_q}{RT})}$

where: A_q is the pre-exponential factor for Qtz (MPa^{-n} s^{-1}); f_h is the water fugacity; σ is the differential stress (MPa); n is the stress exponent; Q_q is the activation energy (J); R is the gas constant (J/K/mol); T is the temperature (K). The contribution of diffusion creep in quartz is considered to come from pressure-solution creep and has been calculated using the flow law for thin-film pressure-solution of den Brok (1998):

(2) $\dot{\varepsilon}_{qps} = C_2 \frac{\rho_f}{\rho_s} \frac{\sigma}{d^3} \frac{VcD_w}{RT}$

where: C_2 is a shape constant; ρ_f and ρ_s are the fluid and solid densities (Kg m^{-3}), respectively; d is the grain size (μm); V is the molar volume (μm^3 mol^{-1}); c is the solubility of the solid in the fluid phase (molar fraction); D_w is the diffusivity of the solid in the grain-boundary fluid film (μm^2 s^{-1}). The flow laws for poly-mineralic aggregates (e.g. sheared myrmekite and mica-free granitoid) have been calculated following the approach of Dimanov and Dresen (2005) and Platt (2015). The method allows

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a poly-mineralic aggregate flow law to be constructed by considering the proportional contribution of the minerals in the aggregate. The resulting flow laws for the polymineralic aggregates can be derived for both a GSS and GSI rheology and are outlined in detail in the supplementary material. In our calculations only quartz and feldspar are considered as minerals of the aggregates. For quartz the flow laws used are those above (equations 1 and 2), while ~~For~~for feldspar, the flow laws of Rybacki et al. (2006) have been used to calculate the contribution of dislocation and diffusion creep, respectively:

$$(3) \; \dot{\varepsilon}_{disl} \; \dot{\varepsilon} = \; A_f f_h \sigma^n \frac{\sigma^n}{d^m} e^{(-\frac{Q_f + p V^{act}}{RT})}$$

$$(4) \; \dot{\varepsilon}_{diff} = \; A_f f_h \frac{\sigma^n}{d^m} e^{(-\frac{Q_f + p V^{act}}{RT})}$$

where: $\dot{\varepsilon}_{disl}$ represents the strain rate component given by dislocation creep; $\dot{\varepsilon}_{diff}$ represents the strain rate component given by diffusion creep; A_f is the pre-exponential factor for feldspar (MPa^{-n} μm^m s^{-1}); d is the grain size (μm); m is the grain-size exponent ~~(m=3 for diffusion creep; m=0 for dislocation creep)~~; p is the confining pressure (MPa); V^{act} is the activation volume (m^3 mol^{-1}). Flow law parameters are listed in Table 1. Details on the derivation of the deformation mechanism maps and on the calculation of the flow laws are given in the online supplementary material. The model approximates the Reuss (iso-strain) conditions (Dimanov and Dresen, 2005).

The flow laws and flow law parameters were estimated for the pressure-temperature conditions of mylonitization of the Rieserferner (450 °C and 0.35GPa; Ceccato, 2018). At these conditions, the calculated water fugacity is f_h = 97 MPa (Pitzer and Sterner, 1994). Fluid density, Qtz solubility and diffusivity in the thin-film (grain boundary) fluid has been calculated following Fournier and Potter (1982) and Burnham et al. (1969). The flow law parameters defined for An$_{100}$ and An$_{60}$ by Rybacki and Dresen (2004) have been adopted for our calculations to simulate different compositions of "granitoid" and myrmekitic feldspars. These are "wet" flow law parameters that have been derived experimentally from deformation of fine grained aggregates of An$_{100}$ and An$_{60}$ containing 0.004 wt% and 0.3 wt% of water, respectively. In our calculations, all the Kfs has been considered as Plg, given the lack of flow law parameters for Kfs (see discussion in Platt, 2015; Viegas et al., 2016). Our calculation includes the contribution of GBS to the bulk strain rate of the feldspar aggregate, which is considered in the flow law parameters adopted here (see discussions in Xiao et al., 2002; Rybacki and Dresen, 2004).

The grain-size vs. differential stress and differential stress vs. strain rate diagrams in Fig. 9 suggest the occurrence of different rheological behaviours that can be interpreted in terms of strain partitioning between aggregates with different "compositions". The results indicate that the three considered types

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of aggregates can be ranked, from the strongest to the weakest, as follows: (i) Qtz-feldspar "granitoid" aggregate; (ii) monomineralic Qtz aggregates; (iii) sheared myrmekite. This ranking is validated by several field and microstructural observations, which highlight the strain localization capability of monomineralic Qtz layers (i.e. Qtz veins) and two-phase microstructural domains (i.e. sheared myrmekite) in granitoid rocks (Pennacchioni, 2005; Pennacchioni and Mancktelow, 2007; Menegon and Pennacchioni, 2010; Pennacchioni and Zucchi, 2013; Pennacchioni et al., 2010; Ceccato et al., 2017). The results of rheological calculation of Plg + Qtz aggregates deforming via diffusion creep (sheared myrmekite) are consistent and comparable with some of the experimental results of Xiao et al., (2002) extrapolated to natural geological conditions (Fig. 9c). The experimental data that best fit our estimated rheological curve are those obtained from triaxial deformation experiments of synthetic very fine-grained wet aggregate of 80 vol% An_{100} Plg (6 µm) + 20 vol% Qtz (10 µm).

~~7~~8. Discussion

The following discussion ~~section~~ is structured ~~by~~in two main parts: firstly, the microstructural processes controlling nucleation and the deformation mechanisms during myrmekite shearing are discussed; then, the results of rheological calculation are discussed ~~at~~in the light of the previously identified deformation mechanisms, in order to give a quantitative ~~view~~estimate of the rheological effects associated with the activity of different deformation mechanisms in mono- and polymineralic domains ~~to the microstructural processes described earlier.~~

~~8~~7.1 Formation and shearing of myrmekite

In the following sections, EBSD data presented earlier are discussed in order to gain new insights on myrmekite nucleation process ~~at~~in the light of previously published works. The possible mechanisms involved during the transition from pristine to sheared myrmekite are then addressed, comparing the evolution of myrmekite to that of similar symplectites during shearing. Then, deformation mechanisms during shearing of myrmekite are finally ~~quantitatively~~identified based on microstructures and ~~addressed by supporting~~ EBSD data.

~~8~~7.1.1 Crystallographic relationship between K-feldspar and myrmekitic phases

The EBSD analysis indicates that the Kfs and the overgrowing myrmekitic Plg have a similar crystallographic orientation, though with some scattering (Fig. 3b; Wirth and Voll, 1987). This suggests the occurrence of a topotactic replacive process where $(100)_{Kfs} \parallel (100)_{Plg}$, $(010)_{Kfs} \parallel (010)_{Plg}$, and $(001)_{Kfs} \parallel (001)_{Plg}$. The scatter in crystallographic orientation between Kfs and myrmekitic Plg is

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interpreted to result from deformation during and after myrmekite formation (see section 8̶6.1.2). The crystallographic orientation of myrmekitic Plg and Qtz was not controlled by neighbour Plg or Qtz grains previously in contact with the Kfs, differently from what is reported by other authors (Stel and Breedveld, 1990; Abart et al., 2014). As observed by Abart et al. (2014), the different myrmekite Qtz

5   vermicules have a similar crystallographic orientation. The anticlustered phase spatial distribution of pristine myrmekite is related to the process of heterogeneous phase nucleation during myrmekite formation (Wirth and Voll, 1987).

8̶7.1.2. Transition from pristine- to sheared myrmekite (plagioclase + quartz aggregates)

The sheared Plg + Qtz aggregates, wrapping Kfs porphyroclasts and elongated into the foliation,
10   resulted from shearing of pristine myrmekite. The transition from pristine to sheared myrmekite was a dynamic process and here we try to constrain the processes involved as inferred from microstructural changes. These microstructural changes included: (i) randomization of Plg CPO observed in pristine myrmekite; (ii) evolution of Plg grain size distribution from heterogeneous (ranging between 3 to 50 µm) in pristine myrmekite, to homogeneous and centred at 7 µm in sheared myrmekite (Figs. 3, 4 and
15   8a); (iii) coarsening of Qtz grains from <3 µm thick vermicules to rounded-to-polygonal grains as large as 10 µm in sheared myrmekite (Fig. 7). The processes of grain size evolution are probably related to the minimization of interfacial energy in the vermicular microstructure of pristine myrmekite (e.g. Odashima et al., 2007; Dégi et al., 2010). Qtz grain coarsening reflects annealing of the pristine vermicular microstructure after the reaction front moved further into the Kfs (Fig. 3a), and was
20   probably aided by dissolution-precipitation processes. Qtz coarsening implies simultaneous grain size refinement of Plg, which probably involved microfracturing, with the development of local micro-cracks in myrmekitic Plg. Misorientation analysis on the few low and high misorientation angle boundaries inside pristine myrmekite (inside myrmekitic Plg) shows abrupt misorientations of as much as 8° across such boundaries, which could be interpreted as either micro-cracks or growth features
25   considering the low internal distortion of grains (Figs. 3, SOM1). Microfractures could have originated from stress concentrations within the 3-D geometrically/mechanically composite structure of myrmekite (see figure 2 of Hopson and Ramseyer, 1990; Dell'Angelo and Tullis, 1996; Xiao et al., 2002). Therefore, the Plg grain size in the incipiently-sheared aggregate may be controlled by the spacing between Qtz vermicules in pristine myrmekite. Myrmekite were then sheared along the
30   mylonitic foliation from the contractional sites around the Kfs porphyroclast. Then, interconnected layers of sheared myrmekite developed from foliation-parallel stretching of isolated myrmekite mantling Kfs during mylonitization (similar to Boullier and Gueguen, 1975).

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8.2. Deformation mechanisms in the Rieserferner mylonites

8.2.1. Sheared myrmekite

These microstructural features of sheared myrmekite are consistent with GSS creep, including fluid-assisted grain boundary sliding (GBS) (Boullier and Gueguen, 1975; White, 1977; Stünitz and Fitz Gerald, 1993; Fliervoet et al., 1997; Jiang et al., 2000; Wheeler et al., 2001; Lapworth et al., 2002; Bestmann and Prior, 2003; Kilian et al., 2011; Menegon et al., 2013). Plg and Qtz of sheared myrmekite both display: (i) a weak CPO; (ii) rare low angle boundaries without systematic pattern of misorientation axis distribution; and (iii) correlated and un-correlated misorientation angle distributions close to the theoretical random-pair distribution. All these features suggest very limited dislocation creep in both minerals (Kruse et al., 2001; Okudaira and Shigematsu, 2012; Miranda et al., 2016). In addition, sheared myrmekite show: (i) fine-grained Plg and Qtz with polygonal, equant to slightly elongated shape (AR<2); (ii) aligned grain boundaries (over the scale of several grain diameters) and common triple/quadruple-junctions; and (iii) anticlustered spatial distribution of Plg and Qtz. These microstructural features are consistent with GSS creep, including fluid-assisted grain boundary sliding (GBS) (Boullier and Gueguen, 1975; White, 1977; Stünitz and Fitz Gerald, 1993; Fliervoet et al., 1997; Jiang et al., 2000; Wheeler et al., 2001; Lapworth et al., 2002; Bestmann and Prior, 2003; Kilian et al., 2011; Menegon et al., 2013).

Phase spatial distribution in deformed bimodal aggregates in mylonites is interpreted to reflect the activity of specific deformation mechanisms (Kruse and Stünitz, 1999; Menegon et al., 2013). In particular, diffusion creep in polymineralic aggregates is commonly accompanied by heterogeneous phase nucleation that promotes phase mixing and a high degree of anticlustering in phase distribution (Kilian et al., 2011; Menegon et al., 2013). The occurrence of Qtz in triple-quadruple junctions and Qtz aggregates elongated orthogonal to the foliation in sheared myrmekite suggest creep cavitation and heterogeneous Qtz nucleation during GSS creep of Plg (Fusseis et al., 2009; Herwegh et al., 2011; Kilian et al., 2011). Heterogeneous phase nucleation in creep cavities led to the anticlustered phase spatial distribution (Fig. 6) (Hiraga et al., 2013; Menegon et al., 2015). The constant Plg grain size of sheared myrmekite may then result from the combination of initial spacing between Qtz vermicules in pristine myrmekite, diffusion creep processes and second-phase grain-boundary pinning during shearing (Herwegh et al., 2011). GSS processes, phase mixing and second-phase grain-boundary pinning inhibit grain growth and stabilizes grain size, hindering the efficiency of dynamic recrystallization processes and self-sustaining the activity of GSS processes.

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87.2.2. K-feldspar tails and neoblasts

Kfs is abundant in the low-strain portions of the mylonite (Fig. 2). Kfs porphyroclasts and tails do not show any CPO or misorientation axis distribution referable to dislocation creep processes (Figs. 4i, SOM2; Menegon et al., 2008, and reference therein). The similar crystallographic orientation between

5 feldspar(s) porphyroclasts and either Kfs tails or fine neoblast aggregates can be explained invoking epitaxial nucleation and growth during dissolution – precipitation (Figs. 4, SOM2). Dissolution – precipitation would be consistent with the Kfs aggregate microstructure observed under CL, which probably reflect either the different chemistry, or the different intragranular strain, observed between magmatic ($Or_{93}Ab_7$) and synkinematic Kfs ($Or_{96}Ab_4$) (Shimamoto et al., 1991; Ramseyer et al., 1992;

10 Götze et al., 1999; Słaby et al., 2008, 2014). The modification of the inherited CPO in fine-grained aggregates could be then related to the occurrence of anisotropic dissolution – precipitation processes and grain boundary sliding during myrmekite shearing (Behrmann and Mainprice, 1987; Menegon et al., 2008, 2013).

78.2.3. Monomineralic quartz layers

15 The microstructures, CL signatures and ~~strong~~ crystallographic preferred orientation of monomineralic Qtz layers indicate deformation by dominant dislocation creep aided by subgrain rotation (SGR) recrystallization (e.g. Fliervoet et al., 1997; Wheeler et al., 2001; Stipp et al., 2002; Bestmann and Pennacchioni, 2015). The misorientation axes distributions suggest the preferential activation of {m}<a> and {r-z}<a> slip systems (e.g. Ceccato et al., 2017 and references therein).

20 The analysis of the grain orientation spread (GOS), to distinguish different generation of relict and/or recrystallized grains (Cross et al., 2017), suggests that there are no meaningful correlations between grain size and average grain distortion. This missing correlation may reflect a non-steady-state Qtz microstructure during a prolonged deformation history or, more likely, the development of the microstructures at different temperature conditions during pluton cooling. The bimodal grain size of

25 recrystallized Qtz includes coarser grains that we infer developed during the relatively high-temperature bulk solid-state deformation of the host granodiorite predating the development of localized shear zones at 450 °C dominated by SGR recrystallization (Ceccato et al., 2017; Ceccato and Pennacchioni, 2018). Coarser grains in Qtz layers (grain sizes from >40 μm) record differential stresses < 40 MPa and strain rates of $10^{-13} – 10^{-14}$ s^{-1} as retrieved applying the grain size paleopiezometer of

30 Cross et al. (2017). Subgrain and finer grains (20-35 μm in diameter) suggest that localized deformation and shearing occurred at differential stresses close to 40-70 MPa and strain rates of $10^{-11} - 10^{-12}$ s^{-1} (Stipp and Tullis, 2003; Cross et al., 2017).

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7.3. The rheology of the Rieserferner mylonites

The rheological effect of transformation of coarse Kfs to fine-grained sheared myrmekite and the transition to an interconnected, weak, fine-grained microstructure (Handy, 1990) is estimated here by investigating the deformational behaviour of different mixtures of Plg and Qtz, in which deformation is accommodated either by dislocation creep or by diffusion creep. Our simplified model does not include Bt, Wmca and Bt + Plg aggregates. Based on the deformation mechanisms identified from the microstructural analysis, deformation mechanisms maps have been calculated and plotted on grain-size vs. differential stress and on differential-stress vs. strain rate diagrams for the following three end-member compositions (Fig. 9):

(i)   monomineralic Qtz layer deforming via both dislocation and diffusion creep (Fig. 9a);

(ii)   sheared myrmekite, modelled as 80 vol% Plg (An$_{60}$) + 20 vol% Qtz deforming via both dislocation creep and grain size sensitive creep (Fig. 9b); the input grain size is 7 μm, identical for both minerals;

(iii)   a mixture of 60% Plg (An$_{100}$) + 40% Qtz assumed as a simplified composition representative of a mica free granitoid rock deforming only by dislocation creep (after referred as "granitoid") (Fig.9c).

The flow law of Hirth et al. (2001) has been used to calculate the dislocation creep component in deformation mechanisms maps for Qtz:

$$(1) \quad \dot{\varepsilon} = A_q f_h \sigma^n e^{\left(-\frac{Q_q}{RT}\right)}$$

where: A_q is the pre-exponential factor for Qtz (MPa^{-n}·s^{-1}); f_h is the water fugacity; σ is the differential stress (MPa); n is the stress exponent; Q_q is the activation energy (J); R is the gas constant (J/K*mol); T is the temperature (K). The contribution of pressure solution creep in Qtz has been calculated following the flow law for thin-film pressure solution of den Brok (1998):

$$(2) \quad \dot{\varepsilon}_{qps} = C_2 \frac{\rho_f}{\rho_s} \frac{\sigma}{d^3} \frac{VcD_w}{RT}$$

where: C_2 is a shape constant; ρ_f and ρ_s are the fluid and solid densities (Kg m^{-3}), respectively; d is the grain size (μm); V is the molar volume (μm^3·mol^{-1}); c is the solubility of the solid in the fluid phase (molar fraction); D_w is the diffusivity of the solid in the grain-boundary fluid film (μm^2·s^{-1}). For feldspar, the flow laws of Rybacki et al. (2006) have been used to calculate the contribution of dislocation and diffusion creep:

(3) $\dot{\varepsilon} = A_f f_h \dfrac{\sigma^n}{d^m} e^{\left(\frac{Q_f + pV^{act}}{RT}\right)}$

where: A_f is the pre-exponential factor for feldspar (MPa^{-n}·μm^m·s^{-1}); d is the grain size (μm); m is the grain-size exponent ($m=3$ for diffusion creep; $m=0$ for dislocation creep); p is the confining pressure (MPa); V^{act} is the activation volume (m^3·mol^{-1}). Flow law parameters are listed in Table 1. The flow laws for poly-mineralic aggregates (e.g. sheared myrmekite and mica-free granitoid) have been calculated following the approach of Dimanov and Dresen (2005) and Platt (2015). Details on the derivation of the deformation mechanism maps and on the calculation of the flow laws are given in the online supplementary material.

The flow laws and flow law parameters were estimated for the pressure-temperature conditions of mylonitization of the Rieserferner (450 °C and 0.35GPa; Ceccato, 2018). At these conditions, the calculated water fugacity is $f_h = 97$ MPa (Pitzer and Sterner, 1994). Fluid density, Qtz solubility and diffusivity in the thin-film (grain boundary) fluid has been calculated following Fournier and Potter (1982) and Burnham et al. (1969). The flow law parameters defined for An$_{100}$ and An$_{60}$ by Rybacki and Dresen (2004) have been adopted for our calculations to simulate different compositions of "granitoid" and myrmekitic feldspars. These are "wet" flow law parameters that have been derived experimentally from deformation of fine grained aggregates of An$_{100}$ and An$_{60}$ containing 0.004 wt% and 0.3 wt% of water, respectively. In our calculations, all the Kfs has been considered as Plg, given the lack of flow law parameters for Kfs (see discussion in Platt, 2015; Viegas et al., 2016). Our calculation includes the contribution of GBS to the bulk strain rate of the feldspar aggregate, which is considered in the flow law parameters adopted here (see discussions in Xiao et al., 2002; Rybacki and Dresen, 2004).

7.3.1. Calculated rheology and strain partitioning in the Rieserferner mylonites

The grain-size vs. differential stress and differential stress vs. strain rate diagrams in Fig. 9 suggest the occurrence of different rheological behaviours that can be interpreted in terms of strain partitioning between aggregates with different "compositions". The results indicate that the three considered types of aggregates can be ranked, from the strongest to the weakest, as follows: (i) Qtz-feldspar "granitoid" aggregate; (ii) monomineralic Qtz aggregates (grain-sizes of 4-10-20-100 μm); (iii) sheared myrmekite. This ranking is validated by several field and microstructural observations, which highlight the strain localization capability of monomineralic Qtz layers (i.e. Qtz veins) and two-phase microstructural domains (i.e. sheared myrmekite) in granitoid rocks (Pennacchioni, 2005; Pennacchioni and Mancktelow, 2007; Menegon and Pennacchioni, 2010; Pennacchioni and Zucchi,

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~~2013; Pennacchioni et al., 2010; Ceccato et al., 2017). The results of rheological calculation of Plg + Qtz aggregates deforming via diffusion creep (sheared myrmekite) are consistent and comparable with some of the experimental results of Xiao et al., (2002) extrapolated to natural geological conditions (Fig. 9c). The experimental data that best fit our estimated rheological curve are those obtained from triaxial deformation experiments of synthetic very fine-grained wet aggregate of 80 vol% An$_{100}$ Plg (6 µm) + 20 vol% Qtz (10 µm).~~

8.3. The effect of myrmekite ~~reaction~~ on strain localization

In the following, the results of rheological calculations are discussed in terms of their implications on strain localization in granitoid rocks. Firstly, we will address the different rheology and strain partitioning at the microstructural scale, considering the calculated rheology for the different mono- and poly-mineralic layers. Then, the effect of increasing myrmekite substitution on the bulk rheology of a granitoid rock is addressed, comparing the rheology of the simplified granitoid rock to that of a granitoid rock with increasing myrmekite substitution.

Our results show that in the Rieserferner mylonites an effective strength contrast between mono- and poly-mineralic ~~aggregates~~layers occurs at the scale of the thin section as a consequence of the different deformation mechanisms. To quantify the effective strength contrast between the modelled layer compositions, we consider two end-member conditions: constant stress and constant strain-rate. Assuming that the differential stress of 40-70 MPa, estimated from the finer grain size of Qtz (from 20 µm to 35 µm), is representative of the bulk flow stress of the mylonite, the Qtz aggregates deforming by dislocation creep (Fig. 9a) would flow at a strain rate of 10^{-11}-10^{-13} s^{-1} whereas sheared myrmekite deforming via diffusion creep would flow at strain rates faster than 10^{-12} s^{-1}, depending on the actual grain size of the aggregate (red transparent area in Fig. 9b). For the grain size range of sheared myrmekite (4-7 µm), the observed strain rates are always faster than 10^{-11} s^{-1}, and for the above defined differential stress range the calculated strain rate is on the order of 10^{-9} s^{-1} (intersection between red transparent area and black box in Fig. 9b). Therefore, assuming constant differential stress conditions, a strain-rate partitioning of 2-4 orders of magnitude is expected between monomineralic Qtz and sheared myrmekite (similarly to Behrmann and Mainprice, 1987). Assuming constant strain rate conditions of 10^{-11} - 10^{-12} s^{-1}, the differential stress calculated for sheared myrmekite deforming via diffusion creep is <45 MPa. Under the constant strain rate assumption, the strength contrast between monomineralic Qtz and sheared myrmekite is not quantifiable; however, the sheared myrmekite are always weaker than monomineralic Qtz deforming via dislocation creep. Strain rates on the order of 10^{-11}-10^{-13} s^{-1} would require grain sizes in the range of 10-100 µm in the sheared myrmekite deforming

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by diffusion creep only (grey shaded areas in Fig. 9b). ~~The deformation mechanisms are here mainly dependent on the composition (mono- vs. poly-mineralic layers) and on the grain size of the aggregates.~~

Figure 9d shows the different curves describing the rheological behaviour of a simplified granitoid rock where Kfs is progressively replaced, up to 20 vol%, by sheared myrmekite. The flow behaviour of the derived granitoid mylonite is represented by the grey curves, and is linear viscous for most of the investigated conditions. The complete consumption of Kfs results in 3-4 orders of magnitude increase of strain rate at differential stress conditions of 70 MPa, (inset of Fig. 9d), i.e. at the maximum stress conditions obtained from quartz paleopiezometry, consistent with experimental observations (Xiao et al., 2002). A similar increase in strain rate is already observed for a 5 vol% of sheared myrmekite in the total rock volume. These results can be compared to the different degree of myrmekite substitution observed along the strain gradient in the shear zone and also could explain the progressive increase in strain toward the ultramylonite with increasing myrmekite substitution (Fig. 2), suggesting positive feedback between strain-induced myrmekite formation and strain accommodation. Dissolution-precipitation creep of Kfs and associated GSS creep in Kfs + Plg + Qtz aggregates have been already described by Behrmann and Mainprice (1987) as an efficient strain accommodation and weakening mechanism in Qtz-feldspar mylonites. In the Rieserferner mylonites, GSS creep of Kfs seems to be dominant in protomylonite, but its role decreases with increasing myrmekite substitution (Fig. 2). The positive correlation between accommodated strain and amount of sheared myrmekite ~~substitution~~ suggests that GSS creep processes in Kfs are however not capable of accommodating strain at rates comparable to those produced by GSS creep in sheared myrmekite.

The effect of myrmekite development in rheological weakening might be overestimated by our calculation, for two main reasons: (i) other weakening mechanisms, that are not considered in our simplified model of granitoid (such as feldspar GSS creep, Bt deformation), may have concurred to deformation; and (ii) at low strain, myrmekite aggregates were initially non interconnected pockets (e.g. Handy, 1994). Strain weakening associated with myrmekite is inferred to become relevant as, with increasing strain and volume fraction of sheared myrmekite, the initially isolate myrmekite are sheared and coalesced into an interconnected network. In the Rieserferner sheared granodiorites an interconnected framework of sheared myrmekite is established in presence of 5 to 7 vol% of myrmekite and is well developed at 10-15 vol% (Fig. 2). Therefore, mylonites containing up to 15 vol% of sheared myrmekite ideally underwent deformation at strain rates of 10^{-10}-10^{-11} s^{-1} and at differential stresses in the range between 14-0 and 70 MPa (transparent red area bracketed by the curve~~s~~ calculated for

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10vol% and 20vol% of myrmekite substitution in Fig. 9d). These mylonites were synkinematic to mylonitic Qtz veins described in Ceccato et al. (2017), for which Qtz paleopiezometry retrieved comparable strain rates of 10^{-11} s^{-1} for 117 MPa differential stress.

Our results show that in the Rieserferner mylonites an effective strength contrast between mono- and poly-mineralic aggregates occurs as a consequence of the different deformation mechanisms.

To quantify the effective strength contrast between the modelled compositions, we consider two end-member conditions: constant stress and constant strain rate. Assuming that the differential stress of 40-70 MPa, estimated from the finer grain size of Qtz (from 20 µm to ~35 µm), is representative of the bulk flow stress of the mylonite, the Qtz aggregates deforming by dislocation creep (Fig. 9a) would flow at a strain rate of 10^{-11}-10^{-13} s^{-1} whereas sheared myrmekite deforming via diffusion creep would flow at strain rates faster than 10^{-12} s^{-1}, depending on the actual grain size of the aggregate (red transparent area in Fig. 9b). For the grain-size range of sheared myrmekite (4-7 µm), the observed strain rates are always faster than 10^{-11} s^{-1}, and for the above defined differential stress range the calculated strain rate is on the order of 10^{-9} s^{-1} (intersection between red transparent area and black box in Fig. 9b). Therefore, assuming constant differential stress conditions, a strain-rate partitioning of 2-4 orders of magnitude is expected between monomineralic Qtz and sheared myrmekite (similarly to Behrmann and Mainprice, 1987). Such strain-rate partitioning could also explain the observed decrease in Qtz grain size from the core of monomineralic layers toward neighbouring sheared myrmekite (Fig. 4).

Assuming constant strain rate conditions of 10^{-11} – 10^{-12} s^{-1}, the differential stress calculated for sheared myrmekite deforming via diffusion creep is <45 MPa. Under the constant strain rate assumption, the strength contrast between monomineralic Qtz and sheared myrmekite is not quantifiable; however, the sheared myrmekite are always weaker than monomineralic Qtz deforming via dislocation creep. Strain rates on the order of 10^{-11}-10^{-13} s^{-1} would require grain sizes in the range of 10-100 µm in the sheared myrmekite deforming by diffusion creep only (grey shaded areas in Fig. 9b).

7.3.2. The effect of myrmekite reaction

Figure 9d shows the different curves describing the rheological behaviour of a simplified granitoid rock where Kfs is progressively replaced, up to 20 vol%, by sheared myrmekite. The flow behaviour of the derived granitoid mylonite is represented by the grey curves, and is linear viscous for most of the investigated conditions. The complete consumption of Kfs results in 3-4 orders of magnitude increase of strain rate, consistent with experimental observations (Xiao et al., 2002). A similar increase

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in strain rate is already observed for a reaction progress factor of $\chi = 0.25$, i.e. for a 5 vol% of sheared myrmekite in the total rock volume. These results can be compared to the different degree of myrmekite substitution observed along the strain gradient in the shear zone and also justify the progressive increase in strain toward the ultramylonite with increasing myrmekite substitution (Fig. 2), suggesting positive feedback between strain-induced myrmekite formation and strain accommodation. Dissolution-precipitation creep of Kfs and associated GSS creep in Kfs + Plg + Qtz aggregates have been already described by Behrmann and Mainprice (1987) as an efficient strain accommodation and weakening mechanism in Qtz-feldspar mylonites. In the Rieserferner mylonites, GSS creep of Kfs seems to be dominant in protomylonite, but its role decreases with increasing myrmekite substitution (Fig. 2). The positive correlation between accommodated strain and myrmekite substitution suggests that GSS creep processes in Kfs are however not capable of accommodating strain at rates comparable to those produced by GSS creep in sheared myrmekite.

The effect of myrmekite development in rheological weakening might be overestimated by our calculation, for two main reasons: (i) other weakening mechanisms, that are not considered in our simplified model of granitoid (such as feldspar GSS creep, Bt deformation), may have concurred to deformation; and (ii) at low strain, myrmekite aggregates were initially non-interconnected pockets (e.g. Handy, 1994). Strain weakening associated with myrmekite is inferred to become relevant as, with increasing strain and volume fraction of sheared myrmekite, the initially isolate myrmekite are sheared and coalesced into an interconnected network. In the Rieserferner sheared granodiorites an interconnected framework of sheared myrmekite is established in presence of 5 to 7 vol% of myrmekite and is well developed at 10-15 vol% (Fig. 2). Therefore, mylonites containing up to 15 vol% of sheared myrmekite ideally underwent deformation at strain rates of 10^{-10}-10^{-11} s^{-1} and at differential stresses in the range between 14 and 70 MPa. These mylonites were synkinematic to mylonitic Qtz veins described in Ceccato et al. (2017), for which Qtz paleopiezometry retrieved comparable strain rates of 10^{-11} s^{-1} for 117 MPa differential stress.

98. Conclusions

Metamorphic reactions contributed importantly to strain weakening within the Rieserferner granitoid mylonites. A primary grain size reduction mechanism was related to the development of myrmekite evolving, with increasing strain, to weak aggregates of Qtz and Plg. Topotactic replacement has been inferred from the coincidence between myrmekitic Plg and parent Kfs grain crystal lattices in pristine myrmekite. Transition from pristine myrmekite to fine-grained sheared myrmekite involved microfracturing, annealing and shearing of the resulting granoblastic aggregate. Sheared myrmekite

consists of fine grained Plg + Qtz aggregates (7 µm and 4 µm in grain size, respectively) that show anticlustered spatial distribution and well-defined shape preferred orientation; Qtz usually occurs at triple- and quadruple-junction between Plg grains. Both Plg and Qtz show weak CPOs and almost uniform misorientation angle distributions. The microstructures of sheared myrmekite suggest that different deformation mechanisms occurred in Plg and Qtz: Plg deformed mainly by GSS creep, whereas dissolution-precipitation and nucleation processes were dominant in Qtz. Myrmekite formation promoted also phase mixing, as the pristine myrmekite microstructure predisposed the development of an "anticlustered" spatial distribution of phases in the recrystallized aggregate. Strong grain size reduction and the nucleation of Plg + Qtz polymineralic aggregates led to a switch in the dominant deformation mechanisms, activating GSS creep processes and triggered phase mixing. GSS processes and phase mixing inhibited grain growth and stabilized grain size, hindering the efficiency of dynamic recrystallization by dislocation creep processes and self-sustaining the activity of GSS processes. Therefore, the formation of myrmekite led to the activation of self-sustaining weakening processes.

Results of rheological calculations show that, at the conditions of Rieserferner mylonitization, sheared myrmekite are several orders of magnitude weaker than both pure Qtz layers and ideal granitoid rock deforming via dislocation creep. Strain-rate partitioning is therefore expected to occur between sheared myrmekite and monomineralic Qtz layers, and the occurrence of ca. 5 vol% of myrmekite could lead to an increase of 3-4 orders of magnitude in strain rate. However, the effective role of myrmekite in rock weakening depends on the evolution of the rock microstructure. Effective weakening requires interconnection of sheared myrmekite layers, which occurs after the development of 10-15 vol% of myrmekite.

This work highlights the importance of metamorphic reactions as grain size reduction mechanisms in feldspar, and their role in localization of ductile deformation via the activation of grain size sensitive creep. The microstructural results and the rheological calculation presented here will be useful for further development of detailed rheological models of feldspar-rich rocks at mid-crustal conditions.

Code availability

The MATLAB script used for rheological calculation is available on request from the first author.

Data availability

Supplementary data are available in Supplementary Online Material (SOM).

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Appendix A: Methods

A.1 EBSD sample preparation and data processing

The thin section was SYTON-polished for ca. 3 hours and carbon coated. All data have been processed and analysed using CHANNEL5 software of HKL Technology, Oxford Instruments. Noise reduction
5 was applied following Bestmann and Prior (2003). Local mis-indexing between Plg and Kfs was resolved by nullifying the subset of selected grains with area $<1\mu m^2$ in each map. Dauphiné twins smaller than 0.5 µm have been interpreted as an error from mis-indexing and were replaced by the average orientation of the neighbouring pixels. The indexed phases and relative symmetry group used for the indexing are: quartz – Trigonal -3m; plagioclase (anorthite) – Triclinic -1; orthoclase –
10 Monoclinic 2/m. Critical misorientation for the distinction between low- and high-angle boundaries have been chosen at 10°. Qtz grain boundaries with 60°±5° of misorientation were disregarded from grain detection procedure, to avoid any contribution from Dauphiné twinning. Plg grain boundaries with 180°±5° of misorientation around [010] were disregarded from grain detection procedure, to avoid any contribution from Albite twinning. The pole figures (one-point-per-grain, where not
15 differently specified) are plotted as equal area, lower hemisphere projections oriented with the general shear zone kinematics reference system (X = stretching lineation; Z = pole to general shear plane/vein boundary); whereas the misorientation axis distributions in sample coordinates are plotted as equal area, upper hemisphere projections. The inverse pole figures for misorientation axis distribution in crystal coordinates are upper hemisphere projections. Contoured projections have constant contouring
20 parameters (Halfwidth: 10°). Contouring lines are given only for the 0.5-10 m.u.d. (multiple of uniform distributions) range.

A.2 Grain size analysis

Grain sizes were obtained from the grain detection routine of the HKL Channel5 Tango software. The grain size was calculated as diameter of the circle with an equivalent area. The minimum cut-off area
25 was set to 1 μm^2 which means that only grains of a size ≥4 or ≥9 pixels (depending on the map acquisition step-size) were considered. Grain size data were represented as area-weighted distributions by plotting frequency against the square-root grain-size-equivalent grain diameters (as in Herwegh and Berger, 2004; Berger et al., 2011). The grain size distribution approaches a Gaussian distribution when plotted in this way, allowing a good estimate of the mean grain size. The geometric mean grain size
30 (red thick line in grain size distribution diagrams) was obtained graphically as the maximum frequency grain size of the distribution curve. ~~The distribution curve (blue line in grain size distribution diagrams)~~

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~~was obtained interpolating distribution data with a 6th degree polynomial equation in Excel-MS Office. Relative frequencies are normalized to 1.~~

A.3 Image analysis

Image analysis of grain shape was performed on both SEM-BSE images and phase maps obtained
5 from EBSD. Quantification of phase amount (vol%) was performed through segmentation of SEM-
BSE images of a whole thin section collected at the Electron Microscopy Centre of the University of
Plymouth. Image processing and thresholding was done with the ImageJ software, and further
processing together with manual correction were applied to improve data quality and to ensure the
correspondence of greyscale ranges with specific mineral phases. Grain boundary images and phase
10 distribution images were obtained directly from EBSD phase maps and grain boundary maps
elaborated by Channel5 (HKL technology). Before the analysis with ImageJ software, images were
manually corrected in order to exclude mis-indexing and non-indexed orientation pixels. Grain
boundaries and phase amount have been quantified by pixel counting.

Author contributions

15 AC, LM and GP developed the initial idea of the study and performed initial exploratory SEM study.
GP collected the samples of Rieserferner mylonites. LM acquired EBSD data. AC performed EBSD
data processing and analysis, and the rheological calculations. LFGM performed cathodoluminescence
analysis. AC prepared the figures and the manuscript with contributions from all the co-authors.

Competing interests

20 The authors declare that they have no conflict of interest.

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Figure and Tables Captions

Table 1. Parameters adopted in the rheological calculations. (a) List of the general parameters adopted in the rheological calculations. (b) Values of flow law parameters adopted in the rheological calculations according to mineral phase and deformation mechanism.

5 **Figure 1.** Microstructures of Rieserferner granodiorite mylonites. (a) Microphotograph (crossed polarizers) showing the alternating layers of recrystallized Qtz, of recrystallized Bt + Plg + Qtz, and of Plg + Qtz. White arrows indicate layers of recrystallized Qtz (upper) and Bt (lower). (b) SEM-BSE image of the area shown in (a). (c) SEM-BSE image of a pristine myrmekite (Myrm) replacing Kfs. Plg + Ttn symplectites (Symp) are indicated by white arrows. (d) SEM-BSE image of the Kfs + Bt

10 tails in strain shadows between two Plg porphyroclasts. Kfs in the strain shadows is in turn replaced by myrmekite (white arrows). (e) SEM-BSE image of a Kfs porphyroclast and of sheared myrmekite. Pristine myrmekite developed on Kfs boundaries parallel to the mylonitic foliation are sheared to form Plg + Qtz aggregates (sheared myrmekite). The white polygon encloses Kfs neoblasts in strain shadows and sheared myrmekite. Plg + Ttn symplectites (Symp) are indicated by white arrows. (f) CL image

15 of (e). Black arrows indicate the Kfs in strain shadows and porphyroclast tails showing low-grey homogeneous CL shades. Note the alteration of the CL signal in Qtz after the EBSD scan (area delimited by white dashed line). (g) Kfs and sheared myrmekite aggregate (particular of the EBSD map of Fig. 3). (h) CL image of (g).

Figure 2. Phase distribution and abundance across a strain gradient in a granodiorite mylonite. (a)

20 Mosaic of SEM-BSE images with the Kfs and the myrmekite + sheared myrmekite coloured in red and pale blue, respectively, and Qtz coloured in black. The yellow rectangles indicate the location of the EBSD maps of Figs. 3, 4, 5 and SOM2. (b) Bar diagram showing the volume amount of Kfs (red bars) and myrmekite (pale blue bars) across the microstructure: PM = protomylonite; M = mylonite; and UM = ultramylonite.

25 **Figure 3.** EBSD map and crystallographic orientation data of incipient myrmekite and parent Kfs. (a) EBSD-derived phase map. The area delimited by dashed polygons represents pristine myrmekite. Grain boundaries are color-coded according to the angle maximum angle of misorientation observed across them. Pole figures for: (b) Kfs grains on which pristine myrmekite nucleated; (c) Plg and (d) Qtz in pristine myrmekite. (e) Enlargment of EBSD map in (a) showing the low-angle (and twin, red)

30 boundaries in plagioclase abutting against quartz vermiculae (indicated by white arrows).

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Figure 4. EBSD map and crystallographic orientation data of pristine and sheared myrmekite of Fig. 1e. (a) EBSD phase map including areas (A, B, C, D) selected for grain size analysis and phase distribution analysis. (b) Pole figures for Qtz from the sheared myrmekite of Area B. Upper row: scattered data. Lower row: contoured data. (c) Misorientation axis distributions for Qtz in sample (upper row) and crystal (lower row) coordinate system. (d) Misorientation angle distribution for Qtz. (e) Pole figures for Plg from sheared myrmekite of Area B. Upper row: scattered data. Lower row: contoured data. In this case, the [100] Plg pole figure is reported in upper hemisphere, where the maximum has been observed. (f) Misorientation axis distributions for Plg in sample (upper row) and crystal (lower row) coordinate system. (g) Misorientation angle distribution for Plg. (h) Pole figures of the crystallographic orientation of Kfs porphyroclasts included in Areas C and E and respective tails. (i) Misorientation axis distributions in sample (upper row) and crystal (lower row) coordinate system for porphyroclasts and tails. (j) Pole figures of the crystallographic orientation of Kfs porphyroclast A and Kfs neoblasts in the strain shadow (Area D). (k) Misorientation axis distributions in sample (upper row) and crystal (lower row) coordinate system for Kfs neoblasts. (l) Grain size distribution for the Kfs neoblasts.

Figure 5. EBSD orientation data and mapping for pure Qtz layers. (a) Orientation map colour coded according to the inverse pole figure for Y-direction reported in the lower right corner. (b) Area-weighted grain size distribution for pure Qtz layer. (b) Pole figures for Qtz [c], <a> and {r} crystallographic elements. (c) Misorientation axis distributions in sample (upper row) and crystal (lower row) coordinate system. (d) Misorientation angle distribution for Qtz.

Figure 6. Image analysis of the phase spatial distribution in myrmekite. The diagram reports phase- and grain-boundary fractions in pristine- and sheared myrmekite. Continuous curves represent the theoretical probability of phase- and grain-boundary fraction as a function of Qtz content expected for a random distribution in a two-phase aggregate. The small maps on the left hand side report one of the analysed areas (Area C. Fig. 4), showing from the top to the bottom the phase map, the Plg grain boundaries, the Qtz grain boundaries, and the Plg-Qtz phase boundaries.

Figure 7. Area-weighted grain size distributions and SPO for Qtz. (a) Grain size distribution for Qtz in incipient myrmekite A in Fig. 4a. (b) Grain size distribution for Qtz in sheared myrmekite B in Fig. 4a. (c) Grain size distribution for Qtz in sheared myrmekite C in Fig. 4a. (d) Grain size distribution for Qtz in monomineralic layer in Fig. 4a. (e) Relative frequency distribution of grain aspect ratio for Qtz. (f) Rose diagram showing the orientation of major axis of Qtz grains, defining a weak SPO. The

distribution curve (blue line in grain size distribution diagrams) was obtained interpolating distribution data with a 6th degree polynomial equation in Excel-MS Office. Relative frequencies are normalized to 1.

Figure 8. Area-weighted grain size distributions and SPO for Plg. (a) Grain size distribution for Plg in myrmekite of Fig. 3. (b) Grain size distribution for Plg in incipient myrmekite A in Fig. 4a. (c) Grain size distribution for Plg in sheared myrmekite B in Fig. 4a. (d) Relative frequency distribution of grain aspect ratio for Plg. (e) Rose diagram showing the orientation of major axis of Plg grains, defining a weak SPO. The distribution curve (blue line in grain size distribution diagrams) was obtained interpolating distribution data with a 6th degree polynomial equation in Excel-MS Office. Relative frequencies are normalized to 1.

Figure 9. Diagrams derived from the calculation of the rheological model explained in the text. Grain size vs. differential stress map with contoured strain rate curves calculated for: (a) Qtz, (b) 80% Plg (An$_{60}$) + 20% Qtz aggregates. (a) The piezometric curve from Stipp and Tullis (2003) (black curve) and Cross et al. (2017) (red curve) are reported. Red and black stars mark the differential stress/strain-rate conditions defined by the grain size observed in pure Qtz layers: (A) 35 µm; (B) 20 µm; (C) 10 µm (Ceccato et al., 2017). (b) ~~A and B marked red polygons represent the differential stress range derived from piezometric calculations on pure Qtz layers (red and black stars along respective piezometric curves).~~ The black dashed line represents the boundary between dislocation and diffusion creep dominated conditions. The black rectangle represents the grain size range (4-7 µm) observed in the sheared myrmekite. The grey semi-transparent polygon defines the field of possible grain-size and differential stress conditions for iso-strain-rate conditions defined from piezometric relations. (c) Log differential stress vs. Log strain rate diagram reporting the curve calculated for pure Qtz with different grain sizes (4 µm, 10 µm, 20 µm, 100 µm), sheared myrmekite, ideal granitoid rock and the curves representing the rheology of pure feldspar aggregates. For comparison, one of the curve obtained from experimental data of Xiao et al., (2002) is reported (black dashed curve). Grey field represents the uncertainties on the experimentally defined rheological curve. (d) Log differential stress vs. Log strain rate diagram reporting the curve calculated for pure Qtz, sheared myrmekite and ideal granitoid rock and the curves representing the rheology of a granitoid (60% An$_{100}$ Plg+ 40% Qtz) with variable amount of sheared myrmekite (80% An$_{60}$ Plg + 20% Qtz). Maximum replacement is limited to 20% of initial feldspar (see text for explanation). Transparent red polygon define the stress-strain rate conditions for 15vol% substitution of myrmekite (see text for explanation). The small figure inset show the logarithm of the ratio between the strain rate of an ideal granitoid rock vs. that of a granitoid with increasing myrmekite substitution at the differential stress of 70 MPa.