Dear Editors,

Dear Reviewers,

With this rebuttal letter, firstly we want to warmly thank the reviewers (Elena A. Miranda and an anonymous reviewer) for the comments and reviews that helped improve the structure of the manuscript. In addition to the changes suggested by the reviewers, major modifications include:

1. The text has been reviewed and polished to simplify sentences, disentangle complicated paragraphs and to delete repetitions or unclear statements.
2. Renumbering of the chapters; the third chapter has been split into two parts (Methods and Microstructures) to facilitate the reader and to improve the structure of the manuscript.
3. Important data from supplementary material have been moved into the main set of figures. Data formerly included in figures SOM2 and SOM4 are now reported in figures 4 and 5.
4. Figure order and numbering have been modified accordingly.
5. The detailed description of rheological calculations applied for the elaboration of deformation mechanisms maps of Figure 9 (former Fig. 10) has been moved to the supplementary online material as suggested.

In addition to the detailed response to Reviewer's comments, attached to this rebuttal comment you will also find the former manuscript of the text with the tracked changes.

Sincerely, on behalf of all co-authors

Alberto Ceccato

Response to Anonymous Referee #1 comments (se-2018-70-RC1)

"…In this paper, there are so many supplementary figures. These figures frequently referred in the main text, and then it is complicated and disturbs our understanding the manuscript. Some supplementary figures should be appeared as figures in the manuscript. The order of figures is somewhat strange. The results of image analysis of grain size and shape (Figs. 6 and 7) should be appeared prior to the results of phase spatial distribution analysis (Fig. 5)."

***Response**: We have included Figures SOM2 and SOM4 in the main text (they are now reported in new Figures 4 and 5), as they indeed show important EBSD data. We prefer to leave the other supplementary Figures in the SOM, as they contain data that complement and expand the figures presented in the main text.*

The figure order reflects the order in which figures are cited in the text. Results of image analysis are described in a paragraph after the EBSD data, therefore the figures follow the same order. The text has been changed in order to respect the order of figures: results of grain size and aspect ratio analyses (Figs. 8 and 9) are now described in a separate section following the description of EBSD data.

"Descriptions of the rheological calculations (section 6.3) are little bit complicated, and then they are not easy to understand. I would like the authors to rewrite and reorganize some sentences in the section 6.3."

***Response**: We have made the effort of maintaining the description of rheological calculation as simple as possible and as complete as possible. To achieve this, we have slightly modified the chapter and introduced subheadings.*

"Although the authors described that micro-cataclastic process or micro-fracturing is a dominant grain size reduction mechanism of plagioclase in the samples analysed here, the microstructural observations indicative of the microcataclastic process or micro-fracturing of plagioclase are not described sufficiently."

***Response**: We agree that referring to microcataclastic processes is misleading and we deleted this term, as there is no evidence in the microstructure of cataclastic deformation. However, the origin of the (few) low angle boundaries within myrmekitic plagioclase (e.g. Figs. 3 and SOM 1a) requires an explanation. Given (1) the abrupt misorientation of up to 8° across such boundaries, and (2) the overall very low internal strain of the myrmekitic plagioclase, we interpret such boundaries as originating as microcracks, and not as subgrain walls resulting from recovery during crystal plastic deformation. We clarified this interpretation in the revised text, Section 6.1.2. This answers also the specific comments (10) and (19).*

Specific comments:

(1) P4, L2-4: In Fig. 2a, there is no identification of myrmekite and K-feldspar for the ultramylonite. Please identify them in Fig. 2a. In Fig. 2b, there are two red bars for the ultramylonite. Is this correct? If so, what do the two different bars represent?

Response*: The identification of myrmekite in the ultramylonitic layer is impossible, given that the fine-grained ultramylonitic matrix is completely mixed and no distinct layers of sheared myrmekite can be identified. K-feldspar in the ultramylonite layer occurs as rare scattered porphyroclast (as now described in the revised manuscript). In the ultramylonitic layer of Fig. 2a, no K-feldspar porphyroclasts can be detected at this magnification, but they are locally present and a good estimate is 1% of the total volume.*

Fig. 2b has been modified and it now contains only one single red bar. This represents the amount (area fraction) of K-feldspar porphyroclasts in the ultramylonite.

(2) P4, L16-17: What is "monocrystalline structure"? This means plagioclase is a single grain? Please clarify the structural characteristics of plagioclase within in each lobe.

Response*: "Monocrystalline structure" means that the plagioclase is a single grain. Monocrystalline substituted with "single grain".*

(3) P4, L25-26: The quartz vermicules do not show any obvious CPO (Fig. 3d).

Response*: Quartz vermicules do not show an overall CPO, but quartz vermicules WITHIN a single myrmekite lobe share a similar crystallographic orientation, as can be inferred from the clustering of few point data in the pole figures of Fig. 3d. The text has been modified accordingly.*

(4) P4, L29: I do not know why "However". Please remove the word.

Response*: "However" deleted.*

(5) P5, L7: Please define "AR"

Response*: AR: Aspect Ratio, now defined in the text.*

(6) P5, L15. P9, L2: At least for me, some plagioclase grains in Area B in Fig. 4a is elongated with the aspect ratio of >2. I would like to see the histogram for aspect ratio of plagioclase grains. Related topic also appears in P9, L2.

Response*: Histograms for aspect ratio added in Figures 7e and 8d for quartz and plagioclase in sheared myrmekite, respectively*.

(7) P5, L18: What does "in crystal direction" mean? It means "in the crystal coordinate system"? If so, please rephrase it.

***Response**: Sentence rephrased. "… misorientation axes in crystal coordinate system are almost uniformly distributed …"*

(8) P5, L19-20: two weak peaks? two strong (or distinct) peaks!

***Response**: "Weak" replaced with "distinct".*

(9) P6, L12-15: If the pole figure of c-axis shows maxima close to Y kinematic direction, the quartz fabric pattern could be assigned to Type-II crossed gridle or single girdle with Y-point maxima. However, the authors described that the quartz fabric pattern was assigned to Type-I crossed girdle (P6, L13).

***Response**: Type-II crossed girdle.*

(10) P8, L18–21: In this sentence, it has been described that grain size refinement of plagioclase involves micro-fracturing as suggested by misorientation analysis on the few low and high misorientation angle boundaries and CPO randomization. However, the authors have not discussed the mechanism of grain size refinement of plagioclase, based on their own microstructural observations. The following paper may be helpful to discuss this issue: Okudaira, T., Shigematsu, N., Harigane, Y. and Yoshida, K. (2017) Journal of Structural Geology, 95, 171–187.

***Response**: We have modified the paragraph trying to clarify the initial process of grain size refinement in plagioclase: "[…]Qtz grain coarsening reflects annealing of the pristine vermicular microstructure after the reaction front moved further into the Kfs (Fig. 3a), and was 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 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). […]". However the discussion here remains rather speculative, since the transition from pristine to sheared myrmekite is a dynamic process impossible to be frozen in a microstructure. The grain size refinement mechanisms during shearing of myrmekite are then discussed in the Section 6.2.1.*

(11) P8,L32 – P9-L1 Kruse et al. (2001) and Miranda et al. (2016) suggested very limited deformation by dislocation creep for plagioclase aggregates in mylonites. As far as I know, Okudaira and Shigematsu (2012, Journal of Geophysical Research, 117, B03210, doi:10.1029/2011.JB008799) only described very limited deformation by dislocation creep for quartz aggregates in natural mylonites.

***Response**: We added a reference to the work of Okudaira and Shigematsu (2012).*

(12) P9, L20: "... do not show any microstructure" may be "... do not show any deformation microstructure".

***Response**: Corrected.*

(13) P10, L9-11: How about the effect of annealing during and or after deformation? The quartz grains associated with myrmekite may be annealed, and then some of quartz grains in monomineralic quartz layer may be also annealed at least partially.

***Response**: Quartz annealing probably occurs only in pristine myrmekite as a consequence of grain boundary area reduction processes and minimization of grain boundary surface energy that is expected to be high in vermicular- and in fine-grained myrmekitic quartz. On the other hand, quartz in monomineralic layers does not show microstructrues commonly considered indicative of annealing, such as 120° triple junctions, the grain shape is commonly elongate and flattened, and the grain size distribution is typically bimodal with a rather wide range. All of this suggests that quartz in the monomineralic layers was not affected by grain boundary area reduction and annealing.*

(14) P11, L2: fh is water fugacity coefficient, not water fugacity itself? What is water fugacity coefficient?

***Response**: Yes, f_h is water fugacity. "Coefficient" is redundant, deleted.*

(15) P14, L2: Why would the composition of plagioclase be assumed to be An100, instead of An60? I do not understand the effect of the plagioclase composition.

***Response**: As reported in Rybacki and Dresen (2004), different compositions of plagioclase lead to different rheological behaviour and flow law properties. Therefore, to mimic the composition contrast between plagioclase in the granitoid rock and myrmekitic plagioclase we have adopted different plagioclase compositions in the rheological calculations for granitoid rock and myrmekite.*

(16) Equations (23), (24) and (25): What does the superscript of 1 mean? Please describe them.

***Response**: All terms of the equations are now explained in the revised text.*

(17) P14, L14: In this figure, the result of diffusion creep for quartz is not necessary.

***Response**: Diffusion creep of quartz in Fig. 8a. This is a deformation mechanisms map for quartz calculated with the reported flow laws for dislocation creep (Hirth et al., 2001) and thin-film pressure-solution creep (den Brok, 1998) adopted in the rheological calculation. It is important to report both deformation mechanism so one can evaluate the conditions at which the transition occurs. Thus, we prefer to keep the diffusion creep field in the figure.*

(18) P14, L18–20: I cannot understand this sentence and Fig. 8c. This sentence means a mixture of plagioclase and quartz (i.e., ideal granitoid rock) deformed by dislocation creep. The other curves in Fig. 8c are necessary? It is very confusing.

Response*: Yes, they are necessary for comparison with the other curves calculated to model the rheology of different aggregates, and for the discussion developed thereafter.*

Quartz and plagioclase are deformed by diffusion creep?

Response*: In the "ideal granitoid rock", plagioclase and quartz are deforming only by dislocation creep.*

The calculation scheme for myrmekite is similar to those for Fig. 8b?

Response*: The calculation scheme for myrmekite is the same as in Fig. 8b, as now specified in the text. However in the case of the "ideal granitoid rock", the flow law is calculated only for dislocation creep.*

The two technical corrections have been incorporated in the revised text.

Response to Elena A. Miranda comments (Referee #2 - se-2018-70-RC2)

1) The methods

“Regarding the methods: the methods (at least the basics) should be in the main body of the manuscript and not in the supplementary material. As written, there are not any methods in the main body. Some of the post-processing details for EBSD can stay in the supplementary material, but the instruments, working conditions, etc., need to be in the main text.”

***Response**: We have moved part of the methods (acquisition of EBSD, CL and EMPA data) to the main text, and left the post-processing details for EBSD and image analysis in the Appendix.*

2) The figures

Regarding the figures: there is a tendency for important and primary EBSD data to be relegated to supplementary figures. […] I recommend moving the supplementary figure EBSD maps out of the appendix, and incorporating them into the main set of figures within the manuscript.”

***Response**: See our reply to a similar comment raised by the anonymous reviewer#1.*

3) Separation of data/interpretation

“… there are a number of interpretive statements located in the geologic setting and in the data sections;”

***Response**: we have accepted all the suggestions by the reviewer and modified the text accordingly.*

4) Flow law derivation: “… whereas the flow law derivation in the main body of the manuscript is extremely detailed, and much of it can be moved to the supplementary material for readers who wish to follow it in more detail.”

***Response**: The detailed description of rheological calculation has been moved to the supplementary material.*

Specific Comments

(1) Abstract P1, L11: “Rephrase for clarity of reading: Here we use EBSD to investigate the microstructure of a granodiorite mylonite…”:

***Response**: Sentence rephrased accordingly*.

(2) P2, L11: Is it important to focus the end of the sentence on weakening of coarse-grained pegmatite? It seems like a distraction given that the focus of the paper is not on pegmatites. It may be best to remove this last phrase so that the sentence is more focused on replacement being a weakening mechanism during ductile deformation, which will provide much more continuity with the next sentence about deformation and shearing of myrmekite.

Response*: The sentence has been rephrased deleting the last part and including the citations preceding brackets*.

(3) P2, L14: There needs to be a stronger link between the sentence that ends with the Viegas et al. reference and the next one that starts with 'Fine grain size'. This should be done with the second sentence (i.e., 'Fine grain size…) so that the weak plag + qtz aggregate is explained as a result of phase mixing and ultramylonites. As written, it does not explicitly link phase mixing and ultramylonites to the samples targeted in this study.

Response*: The sentence has been rewritten in general terms, so that it doesn't need to target our specific sample. However, "the weak plag + qtz" aggregates are not the result of phase mixing in ultramylonites. What we want to show here is different: grain size reduction and phase mixing DUE TO myrmekite formation lead to ultramylonite development.*

(4) P2, L16: Rephrase sentence to make it easier to read: Though the key role of myrmekite in strain localization has been recognized, it has not been accompanied with a quantitative analysis, etc…

Response*: Sentence rephrased accordingly*.

(5) P2, L18: The Introduction should be broken up into at least two paragraphs. Make a new paragraph starting with the sentence: 'Here we present the detailed analysis…' so that the objectives of the work are clearly separated from the background and disciplinary context.

Response*: Paragraph modified accordingly.*

(6) P2, L18-20: The sentence beginning with 'Here we present…' is awkwardly written, and needs to do a better job summarizing the findings of the work. As written, I am not sure if the authors wish to emphasize the two-fold nature of the work (e.g., 1) analysis of myrmekite evolution and 2) grain size reduction and strain localization), or if they mean to portray this as the temporal evolution of some process, i.e., starting with myrmekite evolution and finishing with strain localization in the mylonites. The problem hinges on the part of the sentence between the words 'quartz' and 'grain size'. There either needs to be a conjunction word between 'quartz' and 'grain size' (to? and?) because it's not grammatically correct as written. This is why it is difficult to understand whether 'grain size reduction' just applies to quartz, or to both quartz and plagioclase, and calls into question the intent of the authors.

Response*: The paragraph has been modified accordingly to highlight the two-fold aim of the work.*

(7) P2, L21-23: These sentences are confusing as written, making it hard to understand which mylonites are being studied. If the shear zones nucleate along joints filled with quartz and

epidote, where is the K-spar coming from? Are there two types of shear zones, one set of SZs within the granodiorite and the other set in the quartz- and epidote-filled joints? Does one grade laterally into the other? Please revise for clarity.

Response*: The shear zones in the Rieserferner pluton nucleated on precursor joints and on quartz- and epidote- veins. As described in the referenced papers (Ceccato et al., 2017; Ceccato and Pennacchioni, 2018), homogeneous shear zones developed within quartz veins, whereas heterogeneous shear zones developed in the host rock at the immediate vicinity to joints and epidote-veins. K-feldspar is not included in the mineral assemblage of any of the veins, whereas it forms part of the original magmatic assemblage of tonalite and granodiorite of the Rieserferner pluton. The sentence has been modified to clarify these aspects.*

(8) P3, L5: I recommend you remove the word ‘precursor’. It is implied that the joints are precursory by saying shear zones exploited them.

Response*: Deleted*.

(9) P3. Section 3: Sample description and microstructure. The writing in this section is a little disjointed, with abrupt changes between sentences. Some better linkage between sentences to provide a smoother train of thought would be helpful.

Response*: The section has been splitted into two separate chapters (3. Methods and 4. Microstructures). Details of the analytical techniques have been added to the section.*

(10) P3, L6-9: The sentence beginning with ‘Nucleation…’ is effectively a comparison of the field descriptions with what has been documented in the literature for other locations. Such a comparative statement is best left to the discussion rather than in a section devoted to field description.

Response*: Paragraph deleted*.

(11) P3, L13: I think this section is a little incomplete. There is only a statement describing the shear zones for epidote-filled joints, but the authors state in the previous section that there are also quartz-filled joints upon which shear zones nucleate and also regular joints (no filling) that serve as precursors to shear zones. I recommend that the authors add field descriptions of the shear zones associated with quartz-filled joints and “plain” joints.

Response*: Paragraph has been modified accordingly*.

(12) P3, L15-16: Rearrange the sentence and break into two sentences for clarity: Polished thin sections of granodiorite mylonite were prepared for the study of microstructure and of crystallographic preferred orientation (CPO). The rock chips were cut parallel to the lineation and perpendicular to the shear plane (XZ plane of finite strain ellipsoid).

Response*: Paragraph modified accordingly*.

(13) P3, L18: Specify which minerals were analyzed by microprobe.

***Response**: K-feldspar, Plagioclase. Paragraph modified accordingly.*

(14) P3, L20: The description of EBSD and electron microprobe methods and analytical conditions must be reported in the main body of the manuscript, not hidden in the Appendix.

***Response**: See our reply to the main comment 1).*

(15) P3, L22: The sentence beginning with 'The magmatic plagioclase' is awkwardly written, too long, and hard to understand. It reads like the oscillatory zoning has a range in composition rather than the plagioclase having a range in composition.

***Response**: Sentence rephrased accordingly.*

(16) P3, L24-28: The sentence beginning with 'Various grain size reduction…' is phrased in an interpretive rather than descriptive way. Please rephrase in terms of objective description to be consistent with the "Sample description and microstructure" section title.

***Response**: This is just a list of the different grain size reduction mechanisms identified looking at Rieserferner mylonite under optical microscopy. We prefer to leave this sentence, as it simply describes the observed microstructures.*

(17) P4, L2: There is too abrupt of a change when the data from Figure 2 are introduced. This should be another paragraph, or at least have some more explanatory text about the volume percentage data before it is introduced. Page 4, Line 7-8.

***Response**: The paragraph has been separated from the preceding text.*

(18) P4, L7-8: Why isn't there a photo of the ultramylonites included in Figure 1? All the rest of the mylonites described in this section have a corresponding picture, so this would be good to include for sake of completeness.

***Response**: As ultramylonites are not described and discussed further in the paper, we prefer to not introduce another figure.*

(19) P4, L10: This section is under-developed. These sentences read like a table of contents rather than a data section. It should either be fleshed out into paragraphs where the data are explained, or this brief summary of figure content should be merged into the text in Section 4.1 onward.

***Response**: Section deleted.*

(20) P4, L17: Figure 7a is called out before Figures 3, 4, 5 have even been introduced. The figures should either be renumbered so that the call outs are in numerical order, or these out-

of-order callouts should be removed. There is another error of this nature in Line 18 with respect to Figure 6a.

***Response**: Figure ordering and callout in the text have been modified*.

(21) P5, L1: This sentence is strongly interpretive for a data section. It interprets the origin of the sheared myrmekite, but I suggest keeping the sample/microstructure description objective here and to wait for the Discussion to make the interpretation.

***Response**: We prefer to keep the terminology as it is, to underline from the beginning the strong link between plagioclase + quartz aggregates and myrmekite.*

(22) P5, L9: The callout refers to figure 6e, but there is no 6e (only a-d).

***Response**: Corrected*.

(23) P5, L6: I find the figure callouts hard to follow here. We are flipping between Figure 4 and 6, without 5 being called out yet. Perhaps rearrange the figure order to keep it more organized.

***Response**: Figure ordering and callout in the text have been modified*.

(24) Section 4.3. The paragraphs in this section are lacking strong topic sentences to lead the paragraphs, so that the data are a bit hard to follow. Revise such that a topic sentence gives a summary of the contents of the remainder of the paragraph so that the reader has an idea of what trends are being described.

***Response**: Two topic sentences have been added to the beginning of each paragraph to clarify the content of the paragraphs themselves.*

(25) P5, L28: Only (100) and (010) are planes. The [001] data are directional and should be described as such.

***Response**: The sentence has been modified clarifying which numbers refers to planes and which to crystal directions.*

(26) P7, L6: "Phase spatial distribution…" This sentence is interpretive and the importance of that interpretation is discussed in the next few sentences. I agree this is important, but the interpretation and its importance in a disciplinary context should be in the discussion rather than in the data section.

***Response**: The paragraph have been moved to discussions and in part deleted*

(27) P10, L15-18: Are these differential stresses calculated from grain size piezometry? How are the strain rates calculated? The delivery of the stress values and strain rates is not thorough

enough here; if grain size piezometry is an analysis taken on in the work, it needs to be explicitly stated.

***Response**: Yes, the estimates of differential stress were derived using the recrystallized grain size paleopiezometry (Stipp and Tullis 2003 and Cross et al. 2017). We have rephrased the last sentences of that chapter to clarify that those estimates were derived from the grain size distribution of the quartz domains analysed in this study.*

(28) P10, L24: There is something grammatically incorrect about this sentence; revise to clarify what is meant by the last phrase.

***Response**: Sentence deleted.*

(29) P10, Section 6.3: In the interest of brevity, it might work well to put some of the flow law derivations and calculations into the supplemental online material.

***Response**: The detailed description of rheological calculation has been moved to the supplementary material. However, for the sake of clarity, we have maintained a short introduction to the rheological calculation, describing the flow laws adopted for each phase.*

(30) P11, L11: It is worth noting here that this is a wet plagioclase flow law, and it would be good to quote the amount of water present in these experiments.

***Response**: Yes, we agree. Sentence modified accordingly.*

(31) P15, L5-6: There needs to be a stronger topic sentence than the one that begins Section 6.3.1. As written, it's essentially just a callout to Figure 8, but a more powerful topic sentence would give better direction to the paragraph. The sentence should instead focus on the primary results of the deformation mechanism maps.

***Response**: The sentence has been modified in: "The grain-size vs. differential stress and differential stress vs. strain rate diagrams in Fig. 8 suggest the occurrence of different rheological behaviour that can be interpreted in terms of strain partitioning between aggregates with different "compositions".*

(32) P15, L26: The authors state that they consider both constant stress and constant strain rate conditions, but are there any geologic data from the mylonites that support these assumptions about constant stress/strain rate? This should be justified or explained in a little more detail.

***Response**: Constant strain rate/stress conditions are two end-member conditions that are considered as hypothetical conditions during deformation and the consequences of such conditions are then analysed in the text.*

We accepted all the technical corrections suggested, and modified the text and figures accordingly.

Figure 1: Figure 1a: Label the minerals with the abbreviations qtz, bt, etc., to support the caption and to match Figure 1b.

***Response**: Done.*

Figure 1c: label the myrmekite directly on the figure.

***Response**: Done.*

Figure 1d: the caption refers to K-spar, but only plagioclase is identified here. Is this the correct figure?

***Response**: Labels for Kfs have been added.*

Figure 1f: why is the note about CL image after EBSD scan included? There is no EBSD map area labelled here, so it's hard to understand where in the figure the reader is supposed to look for this. Furthermore, is this an important and necessary point to include? Consider deleting if it's not central to the story.

***Response**: The EBSD map area has now been identified by a dashed white line. It is important to highlight this fact because EBSD scans modify the CL signal for quartz and a possible reader might get confused looking at the CL image.*

Figures SOM1-5. These figures are commonly called out in the text and contain important primary data, so they need to be in the main text with the rest of the figures rather than in supplementary materials. These maps are more insightful on process than just the phase maps in the standard figures, so this is an important change to make.

***Response**: See response to major comment.*

Myrmekite and strain weakening in granitoid mylonites

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Abstract. At mid-crustal conditions, deformation of feldspar is mainly accomplished 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 investigate withuse EBSD (i) to investigate the microstructure of a granodiorite mylonite, developed at ca.~ 420-460-50 °C during cooling of the Rieserferner pluton (Eastern Alps), and (ii) to assess the microstructural processes and the role of weakening associated with myrmekite development. Our analysis shows that the crystallographic orientation of the plagioclase of in pristine myrmekite was controlled by that of the replaced K-feldspar. Myrmekite nucleation resulted in both grain size reduction and anticlustered ordered phase mixing by heterogeneous nucleation of quartz and plagioclase. The fine grain size of sheared myrmekitesheared 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 myrmekitesheared myrmekite), during deformation at 450 °C, show that during mylonitization at 450 °C grain-size-sensitive creep in sheared myrmekitesheared 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 upper continental (felsic) 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., 2015de Bresser et al., 2001, 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). Feldspars locally form the load-bearing framework of ~~continental~~ 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~~; Viegas et al., 2016~~). ~~K-feldspar~~ 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~~quartz~~) and Plg ~~plagioclase~~ (plagioclase) (Becke, 1908; Vernon, 1991). Myrmekite replacement is either related ~~either~~ to ~~K-feldspar~~Kfs chemical instability (Cesare et al., 2002), in some cases involving~~the presence of~~ local metasomatic fluids (Phillips, 1980~~Cesare et al., 2002~~), or triggered by stress concentration and ~~by~~ intracrystalline strain in ~~K-feldspar~~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)~~ and is particularly remarkable when it affects coarse-grained pegmatite (LaTour and Barnett, 1987; Pennacchioni, 2005; Pennacchioni and Zucchi, 2013)~~. Deformation and shearing of myrmekite result in~~to~~ a fine-grained ~~plagioclase~~ Plg + ~~quartz~~ Qtz aggregate, that is manifestly weaker than original coarse ~~K-feldspar~~Kfs (Tsurumi et al. 2003; Ree et al., 2005; Ciancaleoni and Marquer, 2006~~; Viegas et al. 2016~~). In general, a ~~F~~fine grain size and the local ~~occurrence~~ presence of grain boundary aqueous fluid~~s~~ promote phase mixing ~~processes~~ 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 ~~The recognition of the key role of myrmekite in strain localization has not been accompanied with a quantitative analysis~~ of the deformation mechanisms within myrmekite-derived, fine-grained ~~plagioclase~~ Plg + ~~quartz~~ Qtz aggregates.

Here we present ~~the~~ a detailed analysis of myrmekite evolution, from the ~~breakdown~~ nucleation stage within~~ into~~~~of~~ ~~K-feldspar~~Kfs ~~in~~to the development of sheared ~~plagioclase~~ Plg +~~and~~ ~~quartz~~ Qtz aggregates,~~-~~ and of the associated rheological weakening that~~the~~ result~~ed~~~~ing grain size reduction and their role~~ 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 ~~quartz~~ Qtz and Ep (epidote)~~-~~ veins~~,~~ during post-magmatic cooling (Ceccato et al., 2017; Ceccato and Pennacchioni, 2018). The progressive development of granodiorite ~~heterogeneous granodiorite~~ mylonite ~~in the~~

~~granodiorite included~~ was associated with consumption of ~~K-feldspar~~Kfs by myrmekite leading to increasingly interconnected, fine-grained ~~plagioclase~~ Plg + ~~quartz~~ Qtz layers. ~~Selected m~~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 ~~plagioclase~~ Plg + ~~quartz~~ Qtz aggregates; (iii) the deformation mechanisms of pure ~~quartz~~ Qtz layers; (v) the deformation mechanisms of ~~K-feldspar~~Kfs porphyroclasts and of ~~K-feldspar~~Kfs ~~neoblasts~~ new grains during mylonitization. Furthermore, the application of mixed flow laws of the aforementioned deformation mechanisms for polymineralic aggregates allows~~ed~~ ~~the quantification of~~ the ~~extent~~ degree of rheological weakening resulting from ~~the~~ deformation of myrmekite to be quantified.

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 ~~developed~~ exploited~~ing~~ ~~precursor~~ shallowly ESE-dipping joints, and the ~~locally associated~~joint-filling ~~quartz~~ Qtz and ~~epidote~~ Ep veins ~~filling the joints~~ (Ceccato, 2018; Ceccato and Pennacchioni, 2018). ~~Nucleation of ductile shear zones on precursor tabular layers (e.g. dykes, veins) or "surface" discontinuities (joints) has been observed in many granitoid plutons (Adamello: Pennacchioni, 2005; Sierra Nevada: Segall and Simpson, 1986; Pennacchioni and Zucchi, 2013) and in meta-granitoid units (Pennacchioni and Mancktelow, 2007, 2018, and reference therein).~~ The temperature of ductile shearing ~~in the Rieserferner~~ has been estimated at 420-460 °C based on thermodynamic modelling (Ceccato, 2018). ~~Where associated with precursor joints filled with epidote, d~~Ductile shearing along joints and ~~epidote~~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). ~~Whereas~~In contrast, Qtz veins filling the joints~~ductile shearing along quartz-filled joints resulted in~~ sharply localized homogeneous shear~~zones~~ing ~~limited to the thickness of the quartz fillings~~ (Ceccato et al., 2017).

3. Analytical m~~M~~ethods~~, Ssample description and microstructure~~

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

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 ~~via~~ with EBSD were complemented with cathodoluminescence (CL) and microchemical analyses~~ performed with an electron microprobe~~.

C~~athodoluminescence~~L 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 ~~artifacts~~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 (~~K-feldspar~~Kfs and ~~plagioclase~~Plg)~~, epidote and phyllosilicate)~~ beam current. PAP correction program was applied to convert X-ray counts into oxide weight percentages.

~~Mineral names are abbreviated according to~~ ~~abbreviations after Kretz (1983). Detailed description of the EBSD post-processing methods and of the image analysis and analytical conditions are reported in Appendix A. Mineral names are abbreviated according to Kretz (1983).~~

4. Microstructure

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

With increasing strain, ~~there is a decrease in~~ the volume percentage of ~~K-feldspar~~Kfs decreases from 19 vol% (undeformed rock and protomylonite), to 1-6 vol% (rare scattered porphyroclasts in mylonite and ultramylonite) (Fig~~s~~. 2). As counterbalance, ~~there is an increase in~~ the volume percentage of fine-grained myrmekite and derived ~~plagioclase~~Plg + ~~quartz~~Qtz aggregates, increases from 3 vol% (undeformed rock and protomylonite) to as much as 13 vol% (mylonite and ultramylonite) (Fig~~s~~. 2~~b~~). Ultramylonites consist of a fine-grained (ca. 10 µm grain size) well-mixed matrix of ~~quartz~~Qtz, ~~plagioclase~~Plg, ~~biotite~~Bt, ~~epidote~~Ep, ~~K-feldspar~~Kfs, ~~titanite~~Ttn, ~~apatite~~ Ap ± ~~garnet~~ Grt ± Wmca ~~(white mica~~ ~~white mica~~).

~~5~~4. EBSD and cathodoluminescence analysis

~~EBSD maps and crystallographic orientation data are reported in Figs. 3 and 4. Results of phase spatial distribution analysis are reported in Fig. 5. Results of image analysis of grain size and shape are reported in Figs. 6 and 7, whereas a selection of the cathodoluminescence microstructures is reported in the online supplementary material (Fig. SOM xxx2).~~. ~~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 Microscope 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.~~ ~~Cathodoluminescence 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.

54.1 Pristine myrmekite

Characteristics of pPristine myrmekite areshows: (i) the preferential development along grain boundaries of K-feldsparKfs porphyroclast oriented parallel to the mylonitic foliation, despite locally mantling entirely the K-feldspar porphyroclast (Fig. 1b-e); (ii) the lobate shape protruding into the K-feldsparKfs (Fig. 1c); (iii) the monocrystalline single grain structure of plagioclasePlg within each lobe (20 to 50 µm in size: Fig. 7a), embedding vermicular quartzQtz (sections up to 3 µm in equivalent size: Fig. 6a); (iv) the rather constant spacing between theof quartzQtz vermicules of about 3-5 µm across the entire lobe; and (v) the preferential elongation of the quartzQtz vermicules orthogonal to the myrmekite/K-feldsparKfs boundary.

The EBSD analysis of the crystallographic relationships between the K-feldspar and the replacing myrmekitic plagioclase and quartz shows that: (i) K-feldsparKfs and myrmekitic plagioclasePlg commonly show have similar crystallographic orientations ((100)$_{Kfs}$ || ({100)}$_{Plg}$, (010)$_{Kfs}$ || (010)$_{Plg}$, and ({001)}$_{Kfs}$ || (001)$_{Plg}$:; Fig. 3b, c); (ii) the quartzQtz vermicules do not share any crystallographic plane or direction with K-feldsparKfs or myrmekitic plagioclasePlg (Fig. 3b-c-d); (iii) quartzQtz vermicules do not show any obvious CPO, but they within a myrmekite lobe usually have similar a crystallographic preferred orientation within a myrmekite lobe (see encircled clusters in Fig. 3d) (Abart et al., 2014); and (iv) Dauphiné and Albite twins are occasionally observed in quartzQtz and plagioclasePlg, respectively.

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

54.2 Sheared myrmekite: plagioclase + quartz aggregates

Shearing of myrmekite gave rise to PplagioclasePlg + quartzQtz aggregates (± rare K-feldsparKfs and biotiteBt) wrap around K-feldsparKfs porphyroclasts and are elongated into the foliation (Fig. 1e). These aggregates are directly connected to and departmake transition to, and extend into the foliation from, pristine myrmekite, and are hereafter referred to hereafter as sheared myrmekite.

QuartzQtz grains of in sheared myrmekite occur either as isolated single grains at triple/quadruple junctions of between plagioclasePlg grains or, less commonly, as polycrystalline aggregates elongated normal to the foliation (Fig. 4a). ~~The quartz grain size is around 3 µm (Area B in Fig. 4a; Fig. 6b), but locally increases to >10 µm (Area C in Fig. 4a; Fig. 6c). Individual grains show polygonal, equant shapes (aspect ratio AR, ratio of length of long to short axis; 1.5<AR<1.75; Fig. 6e) or a weak shape preferred orientation (SPO) oriented at low angle to the local mylonitic foliation (Fig. 6e). Quartz~~Qtz grains within sheared myrmekite have no CPO (Fig. 4b), show little internal distortion and ~~rarely~~ 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° ~~than a random-pair distribution~~ (Fig. 4d). The uncorrelated misorientation angle distribution approaches the random-pair distribution.

~~Plagioclase grains (average grain size of about 7 µm: Figs. 7b-c) are mainly polygonal and range in shape from almost equant to elongated (1.75<AR<2; Fig. 7d). Elongated grains define an SPO almost parallel to the local mylonitic foliation (Fig.7d for Area B in Fig. 4a). Plagioclase~~Plg grains do not show any obvious CPO (Fig. 4e), and ~~they~~ display little internal distortion and rare low angle boundaries. The low and high angle misorientation axes in crystal coordinate system are almost uniformly distributed ~~in crystal directions~~ (Fig. 4f). Even though very close to random-pair distribution, correlated misorientation distribution exhibits two distinct ~~weak~~ 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 ~~cathodoluminescence (~~CL~~)~~ both myrmekitic ~~plagioclase~~Plg and ~~quartz~~Qtz have a ~~CL~~ grey shade similar to the surrounding non-myrmekitic ~~plagioclase~~Plg and ~~quartz~~Qtz (similar to Hopson and Ramseyer, 1990) (Fig. 1f,h).

54.3 K-feldspar aggregates in strain shadows

In this section, EBSD data are used to describe the relationship between Kfs neoblasts and porphyroclasts. ~~K-feldspar~~Kfs neoblasts occur in strain shadows around feldspar porphyroclasts, as well as dispersed within the sheared myrmekite (Figs. 3a, Area C in Fig. 4a; ~~SOM2a~~5a; ~~Area CE in Fig. 4a;~~ Fig. SOM2). In strain shadows, the orientation of (100), (010)~~,~~ planes and [001] direction ~~planes~~ of the neoblasts is similar to that of the porphyroclast (Fig. ~~SOM2~~4h-j5). ~~The grain size of K-feldspar dispersed within sheared myrmekite is ca. 7 µm, comparable to that of the plagioclase in the surrounding sheared myrmekite (Fig. SOM2a-f). The analysed K-feldspar~~In particular, the ~~K-feldspar~~Kfs neoblasts ~~aggregate~~ show~~s~~ 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. ~~SOM2e~~4k5e).

The grain size of new Kfs grains dispersed within sheared myrmekite is ca. 7 µm, comparable to that of the Plg in the surrounding sheared myrmekite (Fig. 5~~f~~l).

The CL imaging of ~~K-feldspar~~Kfs ~~grains and porphyroclasts~~ highlights a complex microstructure, which is different between new grains and porphyroclasts.~~,~~ The~~in which~~ porphyroclasts ~~exhibit a~~show a homogeneous bright shade overprinted by a complex low-grey CL ~~pattern~~ shade (Fig. SOM3). ~~K-feldspar~~Kfs grains in sheared myrmekite and tails around porphyroclasts show a homogeneous low-grey CL ~~signature~~ shade (Fig. SOM3). ~~K-feldspar~~Kfs aggregates elongated parallel to the foliation and enveloped by sheared myrmekite are characterized by bright irregularly-shaped ~~K-feldspar~~Kfs cores (porphyroclasts) surrounded by low-grey shaded ~~K-feldspar~~Kfs.

5~~4~~.4 Quartz layers along foliation

Monomineralic ~~quartz~~Qtz layers defining the mylonitic foliation (Figs. 3, 4 and ~~SOM46~~5) show a variable grain size, and a shape preferred orientation (SPO)~~,~~ inclined to the foliation consistently with the sense of shear. Dauphiné twin boundaries are widespread (red boundaries in Fig. ~~SOM4a6~~5a). The ~~quartz~~Qtz c-axis CPO defines an asymmetric Type-II girdle roughly normal to the local mylonitic foliation (Fig. ~~SOM4b6~~5b). The pole figures of c-axis and <a> directions show maxima close to the Y and to the X kinematic directions, respectively. Misorientation axis distribution for low angle misorientation (<10°) exhibits a wide maximum close to c-axis and <π–π'> directions in crystal coordinates. These misorientation axes~~y~~ ~~are~~ preferentially cluster close to (but~~oriented~~ slightly off-set from) the Y-kinematic direction in sample coordinates (Fig. ~~SOM4c6~~5c). High angle misorientation axis distributions do not show any clear systematic pattern, except for misorientations around 60°. Misorientation angle distribution (Fig. ~~SOM4d6~~5d) shows two peaks at very low angle misorientations (<10°) and around 60° for correlated misorientations. Un-correlated misorientation angle distribution is close to the random-pair distribution.

~~Quartz 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. 6df and SOM5). The coarser grain sizes (>40 µm) is observed close to the centre of quartz layers. These grains are usually characterized by subgrains ranging is in size between 20 and 35 µm. The smaller grain size (<40 µm) commonly envelope the coarser grains, in addition to prevail at the boundary between monomineralic quartz layers and sheared myrmekite, or around feldspar porphyroclasts (Figs. 3, 4 and SOM5e).~~ CPOs and misorientation data of coarser grains do not differ from those of finer grains. In CL images the ~~quartz~~Qtz layers display an overall homogeneous signature, with lower-grey shades close to inclusions and layer boundaries (Fig. SOM3).

6~~5~~. ~~Image Analyses~~Phase spatial distribution, grain size and aspect ratio

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 ~~quartz~~Qtz. We have analysed the phase spatial distribution of ~~plagioclase~~Plg and ~~quartz~~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 in deformed bimodal aggregates in shear zones is interpreted to reflect the activity of specific deformation mechanisms (Kruse and Stünitz, 1999; Menegon et al., 2013). Dislocation creep usually results in either monomineralic aggregates or clustered phase distributions (Heilbronner and Barrett, 2014). 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).~~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 of the same phase) with those expected for a random distribution of the two phases. We have considered three types of boundaries: (i) ~~plagioclase~~Plg – ~~plagioclase~~Plg grain boundaries; (ii) ~~quartz~~Qtz – ~~quartz~~Qtz grain boundaries; and (iii) ~~plagioclase~~Plg – ~~quartz~~Qtz phase boundaries. The results (Fig. ~~7~~6~~5~~) show that ~~(Fig. 5)~~, in pristine and sheared myrmekite: (i) the surface area fraction of ~~quartz~~Qtz ranges between 0.55-0.75 and 0.55-0.65, respectively; (ii) ~~quartz~~Qtz – ~~quartz~~Qtz grain boundaries occur with a lower probability ~~lower~~ than for a random distribution, indicative of an anticlustered distribution; (iii) ~~plagioclase~~Plg – ~~plagioclase~~Plg grain boundaries occur with a higher probability than for a random distribution indicative of a more clustered distribution; and (iv) ~~plagioclase~~Plg + ~~quartz~~Qtz aggregates display an ~~– ordered/~~anticlustered distribution, with ~~plagioclase~~Plg – ~~quartz~~Qtz phase boundaries occurring with higher probability than for random distribution of phases.

Grain size distributions for Qtz (Fig. ~~8~~7) and Plg (Fig. ~~9~~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. ~~9~~8a) embed Qtz vermicules ~3 µm in equivalent diameter (Fig. ~~8~~7a). In sheared myrmekite, Qtz grain size is around 3 µm (Area B in Fig. 4a; Fig. ~~8~~7b), but locally increases to >10 µm (Area C in Fig. 4a; Fig. ~~8~~7c); i~~. I~~ndividual Qtz grains show polygonal, equant shapes (aspect ratio AR, ratio of long to short axis; 1.5<AR<1.75; Fig. ~~8~~7e) or a weak shape preferred orientation (SPO) oriented at low angle to the local mylonitic foliation (Fig. ~~8~~7e). ~~Plagioclase~~Plg grains (average grain size of about 7 µm: Figs. ~~9~~8~~7~~b-c) are mainly polygonal and range in shape from almost equant to elongated (1.75<AR<2; Fig. 987d). Elongated grains define an SPO almost parallel to the local mylonitic foliation (Fig.987d for Area B in Fig. 4a).

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. 87d and SOM43). The coarser grain sizes (>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 prevail at the boundary between monomineralic Qtz layers and sheared myrmekite, or around feldspar porphyroclasts (Figs. 3, 4 and SOM43e).

76. Discussion

76.1 Formation and shearing of myrmekite

76.1.1 Crystallographic relationship between K-feldspar and myrmekitic phases

The EBSD analysis indicates that the K-feldsparKfs and the overgrowing myrmekitic plagioclasePlg 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 $(100)_{Kfs}$ || ({100)}$_{Plg}$, $(010)_{Kfs}$ || $(010)_{Plg}$, and ({001)}$_{Kfs}$ || $(001)_{Plg}$. The scatter in crystallographic orientation between K-feldsparKfs and myrmekitic plagioclasePlg is interpreted to have resulted from deformation during and after myrmekite formation (see section 6.1.2). The crystallographic orientation of myrmekitic plagioclasePlg and quartzQtz was not controlled by neighbour plagioclasePlg or quartzQtz grains previously in contact with the K-feldsparKfs, 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 quartzQtz 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).

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

The sheared plagioclasePlg + quartzQtz aggregates, wrapping K-feldsparKfs porphyroclasts and elongateding into the foliation, are here interpreted to resulted from shearing of pristine myrmekite. These aggregates are therefore hereafter referred to hereafter as sheared 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 ~~plagioclase~~Plg CPO~~s~~ observed in pristine myrmekite; (ii) ~~refinement~~ evolution of ~~plagioclase~~Plg grain size distribution from ~~scattered~~ heterogeneous ~~in pristine~~ (ranging between 3 to 50 µm) in pristine myrmekite, to homogeneous and centred at 7 µm in sheared myrmekite (Figs. 3, 4 and 98~~7~~a); (iii) coarsening of ~~quartz~~Qtz grains from <3 µm thick vermicules to ~~as large as 10 µm~~ rounded-to-polygonal grains as large as 10 µm in sheared myrmekite (Fig. 87~~6~~). The~~se~~ processes of grain size evolution are probably related to the minimization of interfacial energy in the vermicular microstructure of ~~the~~ pristine myrmekite (e.g. Odashima et al., 2007; Dégi et al., 2010). ~~Quartz~~Qtz grain coarsening ~~occurred as a consequence of~~reflects annealing of the pristine vermicular microstructure after the reaction front moved further into the ~~K-feldspar~~Kfs (Fig. 3a), and was probably aided by dissolution-precipitation processes. ~~Quartz~~Qtz coarsening implies simultaneous grain size refinement of ~~plagioclase~~Plg, which probably involved ~~both annealing and~~ micro~~-~~fracturing, with the development of local micro-cracks in myrmekitic Plg.~~:~~, ~~as suggested by~~ M~~m~~isorientation analysis on the few low and high misorientation angle boundaries inside pristine myrmekite (inside myrmekitic Plg) ~~and CPO randomization~~ shows abrupt misorientations of ~~up to~~as much as 8° across such boundaries, which ~~given the low internal distortion of grains~~ could be interpreted as either micro-cracks or growth features considering the low internal distortion of grains (Figs. 3, SOM1~~a~~). 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. ~~Annealed~~ M~~m~~yrmekites ~~are~~ were then sheared along the mylonitic foliation from the contractional sites around the ~~K-feldspar~~Kfs porphyroclast. Then, interconnected layers of sheared myrmekite developed from foliation-parallel stretching of isolated myrmekite mantling ~~K-feldspar~~Kfs during mylonitization (similar to Boullier and Gueguen, 1975).

7~~6~~.2. Deformation mechanisms in the Rieserferner mylonites

7~~6~~.2.1. Sheared myrmekite

~~Plagioclase~~Plg and ~~quartz~~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 ~~deformation by~~ dislocation creep in both minerals (Kruse et al., 2001; Okudaira and Shigematsu, 2012; Miranda et al., 2016). In addition, ~~the~~ sheared myrmekites show: (i) fine-grained ~~plagioclase~~Plg and ~~quartz~~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 ~~plagioclase~~Plg and ~~quartz~~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 shear zones~~~~of~~in mylonites is interpreted to reflect the activity of specific deformation mechanisms (Kruse and Stünitz, 1999; Menegon et al., 2013). ~~Dislocation creep usually results in either monomineralic aggregates or clustered phase distributions (Heilbronner and Barrett, 2014).~~ In particular, ~~D~~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 ~~quartz~~Qtz in triple-quadruple junctions and ~~quartz~~Qtz aggregates elongated orthogonal to the foliation in sheared myrmekite suggest ~~the activity of~~ creep cavitation and heterogeneous ~~quartz~~Qtz nucleation during GSS creep of ~~plagioclase~~ 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 ~~observed in sheared myrmekite~~ (Fig. 7~~65~~) (Hiraga et al., 2013; Menegon et al., 2015). The constant ~~plagioclase~~Plg grain size of sheared myrmekite may then result from the combination of initial spacing between ~~quartz~~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 ~~pinnng~~pinning inhibit grain growth and stabilizes grain size, hindering the efficiency of dynamic recrystallization processes and self-sustaining the activity of GSS processes.

7~~6~~.2.2. K-feldspar tails and neoblasts

~~K-feldspar~~Kfs is abundant in the low-strain portions of the ~~analysed~~ mylonite (Fig. 2). ~~K-feldspar~~Kfs porphyroclasts and tails do not show any ~~deformation microstructure,~~ CPO or misorientation axis distribution referable to dislocation creep processes (Figs. ~~SOM2c5c~~4i, SOM2; Menegon et al., 2008, and reference therein). The similar crystallographic orientation between feldspar(s) porphyroclasts and either ~~K-feldspar~~Kfs tails or fine neoblast aggregates can be explained invoking epitaxial nucleation and growth during dissolution – precipitation (Figs. ~~SOM25~~4, SOM2). Dissolution – precipitation would be consistent with the ~~K-feldspar~~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 K-feldsparKfs ($Or_{96}Ab_4$) (Shimamoto et al., 1991; Ramseyer et al., 1992; 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 slidingGBS/rigid body rotation during myrmekite shearing (Behrmann and Mainprice, 1987; Menegon et al., 2008, 2013).

76.2.3. Monomineralic quartz layers

The microstructures, CL signatures and strong crystallographic preferred orientation of monomineralic quartzQtz 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).

The analysis of the grain orientation spread (GOS), useful 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 quartzQtz 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 recrystallized quartzQtz 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 quartzQtz layers (grain sizes from >40) record differential stresses < 40 MPa and strain rates of 10^{-13} – 10^{-14} s^{-1} as retrieved applying the grain size paleopiezometer of 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).

76.3. The rheology of the Rieserferner mylonites

The rheological effect of transformation of coarse K-feldsparKfs 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 plagioclasePlg and quartzQtz, in which deformation is accommodated either deforming viaby different contribution of dislocation -creep creep andor by diffusion creep. Our simplified model does not include biotiteBt,

~~white mica~~Wmca and ~~biotite~~Bt + ~~plagioclase~~Plg aggregates. Based on the deformation mechanisms ~~that we~~ identified from ~~our~~~~Our simplified model does not include biotite, white mica and biotite + plagioclase aggregates. According to the~~ the ~~above defined~~ microstructural analysis ~~data and defined deformation mechanisms~~, 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. ~~10~~9~~8~~):

(i) monomineralic ~~quartz~~Qtz layer deforming via both dislocation and diffusion creep (Fig. ~~10~~9~~8~~a);

(ii) sheared myrmekite, modelled as 80 vol% ~~plagioclase~~Plg (An_{60}) + 20 vol% ~~quartz~~Qtz deforming via both dislocation creep and grain size sensitive creep (Fig. ~~10~~9~~8~~b); the input grain size is 7 µm, identical for both minerals;

(iii) a mixture of 60% ~~plagioclase~~Plg (An_{100}) + 40% ~~quartz~~Qtz assumed as a simplified composition representative of a mica-free granitoid rock deforming only by dislocation creep (after referred as "granitoid") (Fig.~~10~~9~~8~~c).

The flow law of Hirth et al. (2001) has been ~~adopted~~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 pressure-~~-~~solution creep in Qtz has been calculated following 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}). For feldspar, the flow laws of Rybacki et al. (2006) have been used to calculate the contribution of dislocation and diffusion creep:

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

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-phase 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 bulk strain rate ($\dot{\varepsilon}_{bulk}$) of a mineral aggregate is given by:

(1) $\dot{\varepsilon}_{bulk} = \dot{\varepsilon}_{Dist} + \dot{\varepsilon}_{Diff}$

where: $\dot{\varepsilon}_{Dist}$ and $\dot{\varepsilon}_{Diff}$ represents the strain rates of dislocation creep and diffusion creep of mineral components, respectively.

Quartz. The dDeformation mechanisms map of Fig. 8a has been calculated as follows. The flow law of Hirth et al. (2001) has been used to calculate the contribution of dislocation creep of quartz:

(2) $\dot{\varepsilon}_{q-Dist} = A_q f_h \sigma^n e^{\left(-\frac{Q_q}{RT}\right)}$

where: A_q is the pre-exponential factor for quartz (MPa^{-n} s^{-1}); f_h is the water fugacity coefficient; 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). Following Platt (2015), the flow law of den Brok (1998) for thin-film model of pressure-solution has been used to calculate the contribution of pressure-solution to quartz deformation:

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

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}).

Feldspars. The flow laws of Rybacki et al. (2006) have been used to calculate the contribution of dislocation and diffusion creep of feldspar:

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

(5) $\dot{\varepsilon}_{f-Dist} = A_f f_h \sigma^3 e^{\left(-\frac{Q_f + pV^{act}}{RT}\right)}$

(6) $\dot{\varepsilon}_{f-Diff} = A_f f_h \frac{\sigma}{d^3} e^{\left(-\frac{Q_f + pV^{act}}{RT}\right)}$

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}).

Poly-phase aggregates. Deformation mechanisms mapsDeformation mechanisms maps and rheological calculations for shearedpoly-phase aggregates (feldspar + quartz, i.e. sheared myrmekite and granitoid rock, Fig. 8b-c) myrmekite were calculated following the self-consistent approach presented in Dimanov and Dresen (2005) and Platt (2015). The flow law for the poly-phase aggregate is the following:

(7) $\dot{\varepsilon}_{bulk} = \dot{\varepsilon}_{Dist} + \dot{\varepsilon}_{gps} = A_a f_h \sigma^{n_a} e^{\left(-\frac{Q_a}{RT}\right)} + \frac{\sigma}{2\mu_a}$

;The in which flow law parameters A_a, n_a, Q_a for the "dislocation creep" component (first term of the equation) poly-phase aggregate deforming via dislocation creep are recalculated as follows:

(87) lLog$_{10}$ $n_a = \phi_1 \log_{10} n_1 + \phi_2 \log_{10} n_2$

(98) $Q_a = [Q_2(n_a - n_1) - Q_1(n_a - n_2)]/(n_2 - n_1)$

(109) lLog$_{10}$ $A_a = [\log_{10} A_2(n_a - n_1) - \log_{10} A_1(n_a - n_2)]/(n_2 - n_1)$

where: n_a is the stress exponent for dislocation creep of the two-phase mixture; ϕ_i is the volume fraction of the phase i; n_i is the stress exponent of the i phase; Q_a is the dislocation creep activation energy for the aggregate (J); Q_i is the activation energy for the i phase (J); A_a is the pre-exponential factor for the aggregate (MPa^{-n} µm^{m} s^{-1}); A_i is the pre-exponential factor for the i phase (MPa^{-n} µm^{m} s^{-1}). In order to account for water fugacity and activation volumes parameters in feldspar flow laws (Rybacki and Dresen, 2006), we implemented the model of Platt (2015), which includes the activation volume for feldspars in the calculation of the aggregate activation energy Q_a, as follows:

(110) $Q_a = [(Q_f + pV^{act})(n_a - n_Q) - Q_Q(n_a - n_f)] / (n_f - n_Q)$

where: p is the confining pressure (MPa); V^{act} is the activation volume for feldspars (m^3/mol). Water fugacity coefficients were integrated in the resulting flow law of sheared myrmekitepoly-phase aggregates deforming by dislocation creep:

(121) $\dot{\varepsilon}_{Dist} = A_a f_h \sigma^{na} e^{(-\frac{Q_a}{RT})}$

The flow law for sheared myrmekite deforming by diffusion creep (plagioclase) and thin-film pressure solution (quartz) has been calculated, Ffollowing the approach of Dimanov and Dresen (2005) and Platt (2015), the second term of the equation representing the contribution of "diffusion creep" has been calculated by considering pressure-solution (in quartz) and diffusion creep (in feldspar) to contribute linearly to the bulk viscosity of the aggregate, μ_a:

(132) $3\mu_a{}^2 + [2(\mu_q+\mu_f) - 5(\phi_q\mu_q + \phi_f\mu_f)]\mu_a - 2\mu_q\mu_f = 0$

where

(143) $\mu_q = \frac{\sigma}{2\dot{\varepsilon}_{qps}}$

is the viscosity of quartz deforming via pressure-solution processes calculated following the thin-film model of den Brok (1998); and

(154) $\mu_f = \frac{\sigma}{2\dot{\varepsilon}_{f-diff}}$

is the viscosity of feldspar deforming via diffusion creep. Therefore, the deformation mechanism maps of the sheared myrmekite have been calculated using the following flow law:

(15) $\dot{\varepsilon}_{bulk} = A_a f_h \sigma^{n_a} e^{(-\frac{Q_a}{RT})} + \frac{\sigma}{2\mu_a}$

The rheological modelling of poly-phase aggregates containing more than two -rheological phases (e.g. a granitoid composed of plagioclase + quartz + myrmekite, Fig. 8d) has been performed iteratively applying iteratively the calculation of Platt (2015). For example, for a mixture composed of ϕ_X, ϕ_Y and ϕ_Z volume fractions of the phases X (plagioclase), Y (quartz), and Z (sheared myrmekite):

(i) Firstly, n_{XY}, Q_{XY}, A_{XY} flow law parameters for the XY two-phase mixture are calculated following equations (87), (98) and (109), adopting the volume fractions ϕ_{X1} and ϕ_{Y1} defined as follows:

(16) $\phi_{X1} = \phi_X / (1 - \phi_Z)$; $\phi_{Y1} = \phi_Y / (1 - \phi_Z)$.

(ii) Then for the calculation of the three-phase mixture flow law parameters n_{XYZ}, Q_{XYZ}, A_{XYZ}, considering the three-phase mixture as the result of mixing between phases "XY" and Z, volume fractions are recalculated as follow:

(17) $\phi_{XY} = \phi_X + \phi_Y$; $\phi_Z = \phi_Z$.

and the parameters are calculated as follow:

(18) $n_{XYZ} = 10\text{^}(\phi_{XY} \log_{10} n_{XY} + \phi_Z \log_{10} n_Z)$

(19) $Q_{XYZ} = [Q_Z(n_{XYZ} - n_{XY}) - Q_{XY}(n_{XYZ} - n_Z)]/(n_Z - n_{XY})$

(20) $A_{XYZ} = 10\text{^}[\log_{10} A_Z(n_{XYZ} - n_{XY}) - \log_{10} A_{XY}(n_{XYZ} - n_Z)]/(n_Z - n_{XY})$.

For the calculation of the rheology of an aggregate in which dislocation and diffusion creep contribute in different proportions to the total strain rate (granitoid rock including a variable amount of myrmekite, see Discussion below), a limiting factor θ has been introduced in equation (715). For example, for an aggregate in which diffusion creep is limited to a specific volume proportion of phases:

(21) $$\dot{\varepsilon}_{bulk} = A_a f_h \sigma^{n_a} e^{\left(-\frac{Q_a}{RT}\right)} + \theta_{diff} \frac{\sigma}{2\mu_a}$$

where θ_{diff} represents the volume fraction of the phases undergoing diffusion creep in the aggregate. To consider the progressive transformation of feldspar into myrmekite with increasing strain, differential stress vs. strain rate curves have been calculated for a "granitoid" aggregate with increasing vol% of myrmekite substituting for feldspar (Fig. 8c). The progression of the reaction is quantified by the reaction progress factor χ. The maximum volume percentage of feldspar substitution has been limited to

(22) $\phi_{MAX} = 20$ vol% ;

the average concentration of K-feldspar in granite and granodiorite. For χ=0 (no myrmekite), the rock is composed by of 60 vol% plagioclase An_{100} and 40 vol% quartz. For χ>0, plagioclase An_{100} (representing K-feldspar) is increasingly replaced by myrmekite. Myrmekite ϕ_{Myrm}, plagioclase ϕ_{Plg} and quartz ϕ_{Qtz} volume proportions in the rock are then re-calculated respectively as follows, respectively:

(23) $\phi_{Myrm}{}^{1} = \chi * \phi_{MAX}$;

(24) $\phi_{Plg}{}^{1} = \phi_{Plg} - \chi * \phi_{MAX}$;

(25) $\phi_{Qtz}{}^{1} = \phi_{Qtz}$

The calculation of the rheology of a granitoid rock with variable amount of sheared myrmekite takes into account The calculations represent the case in which grain size sensitive creep occurs only in WHERE??? sheared myrmekite, whereas granitoid quartz and feldspars deform only by dislocation creep. Therefore, the contribution of diffusion creep to bulk viscosity in equation (21) is proportional to

(26) $\theta_{diff} = \chi * \phi_{MAX}$

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 compositions (Fig. 8):

(i) monomineralic quartz layer deforming via both dislocation and diffusion creep (Fig. 8a);
(ii) sheared myrmekite, modelled as 80 vol% plagioclase (An_{60}) + 20 vol% quartz deforming via both dislocation creep and grain size sensitive creep (Fig. 8b); the input grain size is 7 μm, identical for both minerals;
(iii) a mixture of 60% plagioclase (An_{100}) + 40% quartz assumed as a simplified composition representative of a mica-free granitoid rock deforming only by dislocation creep (after referred as "granitoid") (Fig.8c);

The above general flow laws and flow law parameters are 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, quartzQtz 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 obtainedderived experimentally from deformation of fine grained aggregates of An_{100} and An_{60} containing, respectively, 0.004 wt% and 0.3 wt% of water, respectively. In our calculations, a All the K-feldsparKfs has been considered as plagioclasePlg, given the lack of flow law parameters for K-feldsparKfs (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~~6~~.3.1. Calculated rheology and strain partitioning in the Rieserferner mylonites ~~Relative strength, rheological ranking and strain localization~~

The grain-size vs. differential stress and differential stress vs. strain rate diagrams in Fig. ~~10~~9~~8~~ suggest the occurrence of different rheological behaviours that can be interpreted in terms of strain partitioning between aggregates with different "compositions". ~~for the three above defined aggregates are shown in Fig. 8. Flow law parameters are listed in Table 1.~~ The results indicate that the three considered types of aggregates can be ranked, from the strongest to the weakest, as follows: (i) ~~quartz~~Qtz-feldspar "granitoid" aggregate; (ii) monomineralic ~~quartz~~Qtz aggregates (grain sizes of 4-10-20-100 μm); (iii) sheared myrmekite. ~~Nucleation of ductile shear zones on precursor tabular layers (e.g. dykes, veins) or "surface" discontinuities (joints) has been observed in many granitoid plutons (Adamello: Pennacchioni, 2005; Sierra Nevada: Segall and Simpson, 1986; Pennacchioni and Zucchi, 2013) and in meta-granitoid units (Pennacchioni and Mancktelow, 2007, 2018, and reference therein).~~ This ranking is ~~consistent and~~ validated by several field and microstructural observations, ~~that~~ which highlight the strain localization capability of monomineralic ~~quartz~~Qtz layers (i.e. ~~quartz~~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 ~~plagioclase~~Plg + ~~quartz~~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 ~~temperatures~~ conditions (Fig. ~~10~~9~~8~~c). 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% ~~quartz~~Qtz (10 μm). ~~In addition, this rheological ranking supports the interpretation that quartz grains inside pristine myrmekite deforming via dissolution – precipitation creep may behave as strong inclusions compared to feldspar grains deforming via diffusion creep; around these strong inclusions stress can concentrate and trigger microfracturing in the surrounding plagioclase.~~

~~These~~ Our results show that in the Rieserferner mylonites an effective strength contrast ~~occur~~ between ~~the host rock,~~ 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: ~~both~~ constant stress and constant strain-rate conditions. Assuming that Tthe differential stress of 40-70 MPa, estimated from the finer grain size of quartzQtz (20-35 µm), is can be considered representative of the bulk flow stress of the mylonite, the quartzQtz aggregates deforming by dislocation creep (Fig. 9108a) would flow at. At constant stress conditions, such differential stress corresponds to a strain rate of 10^{-11}-10^{-13} s^{-1} whereasof the quartz aggregates deforming by dislocation creep (Fig. 8a). At such differential stress, a 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. 1098b). 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. 1098b). Therefore, assuming constant differential stress conditions, a strain-rate partitioning of 2-4 orders of magnitude is expected between monomineralic quartzQtz and sheared myrmekite (similarly to Behrmann and Mainprice, 1987). Such strain-rate partitioning at constant stress could also explain the observed decrease in quartzQtz 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}, tThe differential stress, calculated for sheared myrmekite deforming via diffusion creep, at constant strain rate conditions of 10^{-11} – 10^{-12} s^{-1}, is always <45 MPa. Under the constant strain rate assumption, the strength contrast between monomineralic quartzQtz and sheared myrmekite is not quantifiable; however, the sheared myrmekite are always weaker than monomineralic quartzQtz deforming via dislocation creep. Strain rates in 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. 1098b).

76.3.2. The effect of myrmekite reaction

Figure 9d 109d shows the different curves describing the rheological behaviour of a simplified granitoid rock where K-feldsparKfs 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 K-feldsparKfs results in 3-4 orders of magnitude increase of strain rate, consistent with experimental observations (Xiao et al., 2002). A similar increase in strain rate is already observed for a reaction progress factor of χ = 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 ~~K-feldspar~~Kfs and associated GSS creep in ~~K-feldspar~~Kfs + ~~plagioclase~~Plg + ~~quartz~~Qtz aggregates have been already described by Behrmann and Mainprice (1987) as an efficient strain accommodation and weakening mechanism in ~~quartz~~Qtz-feldspar mylonites. In the Rieserferner mylonites, GSS creep of ~~K-feldspar~~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 ~~K-feldspar~~Kfs are however not capable of accommodating strain at rates comparable to those produced by GSS creep in sheared myrmekite.

The effect~~ive role~~ of ~~small volume fraction of~~ myrmekite development in rheological weakening ~~of the Rieserferner granitoid during mylonitization~~ 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, ~~biotite~~Bt deformation), may have concurred ~~during~~ to ~~homogeneous~~ deformation ~~of the granitoid rock that are not considered in our simplified model of granitoid (such as feldspar GSS creep, biotite recrystallizationdeformation)~~; and (ii) at low strain, myrmekite aggregates were initially ~~occurred into scattered~~ non interconnected pockets (e.g. Handy, 1994). Strain weakening associated with myrmekite is inferred to become relevant as~~; it is only,~~ with increasing strain and ~~increasing~~ volume fraction of sheared myrmekite, ~~that these~~the initially isolate ~~pockets~~ myrmekite are sheared and coalesced ~~to form an~~into an interconnected ~~weak layer microstructure~~network. In the Rieserferner ~~mylonites~~ sheared granodiorites an ~~effective~~ interconnect~~ion~~ed framework of sheared myrmekite is ~~already developed~~established in presence of 5 to 7 vol% of myrmekite and is ~~particularly~~ 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 ~~quartz~~Qtz veins described in Ceccato et al. (2017), for which ~~quartz~~Qtz paleopiezometry retrieved comparable strain rates of 10^{-11} s^{-1} ~~developed under~~for 117 MPa differential stress ~~(10 µm of grain size)~~.

8~~7~~. Conclusions

Metamorphic reactions contributed importantly to strain weakening within the Rieserferner granitoid mylonites. A primary grain size reduction mechanism ~~is~~ was related to the development of myrmekite evolving, with increasing strain, to weak aggregates of ~~quartz~~Qtz and ~~plagioclase~~Plg. Topotactic replacement has been inferred from the coincidence between myrmekitic ~~plagioclase~~Plg and parent ~~K-feldspar~~Kfs grain crystal lattices in pristine myrmekite. Transition from pristine myrmekite to fine-grained sheared myrmekite involved micro~~-~~fracturing, annealing and shearing of the resulting granoblastic aggregate. Sheared myrmekite consists of fine grained ~~plagioclase~~Plg + ~~quartz~~Qtz aggregates (7 µm and 4 µm in grain size, respectively) that show ~~ordered (~~anticlustered~~)~~ spatial distribution and well-defined shape preferred orientation; ~~quartz~~Qtz usually occurs at triple- and quadruple-junction between ~~plagioclase~~Plg grains. Both ~~plagioclase~~Plg and ~~quartz~~Qtz show weak CPOs and almost uniform misorientation angle distributions. The microstructures of ~~S~~sheared myrmekite ~~microstructural features~~ suggest that different deformation mechanisms occurred in ~~plagioclase~~Plg and ~~quartz~~Qtz: ~~plagioclase~~Plg deformed~~s~~ mainly by GSS creep, whereas dissolution~~-~~-precipitation and nucleation processes ~~are~~ were dominant in ~~quartz~~Qtz. Myrmekite formation promoted~~s~~ 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 ~~plagioclase~~Plg + ~~quartz~~Qtz polymineralic aggregates le~~a~~d 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~~s~~ grain size, hindering the efficiency of dynamic recrystallization processes and self-sustaining the activity of GSS processes. Therefore, the ~~stress-induced~~ formation of myrmekite le~~a~~d 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 ~~quartz~~Qtz layers and ~~than an~~ ideal granitoid rock deforming via dislocation creep. Strain-rate partitioning is therefore expected to occur between sheared myrmekite and monomineralic ~~quartz~~Qtz layers, and the occurrence of ca.~~,~~ 5 vol% of myrmekite ~~would~~ could lead to an increase ~~in strain rate~~ of 3-4 orders of magnitude in strain rate. However, the effective role of myrmekite in rock weakening ~~is however~~ depend~~ent~~s on the evolution of the rock microstructure. Effective weakening ~~need~~ requires ~~for~~ interconnection of sheared myrmekite layers, ~~that~~ which occurs after the development of 10-15 vol% of myrmekite.

This work ~~once again~~ highlights the importance of metamorphic reactions ~~and micro-cataclastic processes~~ 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 ~~(continental crust 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).

Appendix A: Methods

A.1 EBSD ~~analysis~~sample preparation and data processing

~~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 Microscope Centre of Plymouth University.~~ The thin section was SYTON-polished for ca. 3 hours and carbon coated. ~~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.~~ All data have been processed and analysed using CHANNEL5 software of HKL Technology, Oxford Instruments. Noise reduction was applied following Bestmann and Prior (2003). Local mis-indexing between ~~plagioclase~~ Plg and ~~K-feldspar~~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 – Monoclinic 2/m~~; clinozoisite, biotite and garnet have been indexed where present, but orientation data have not been analysed~~. Critical misorientation for the distinction between low- and high-angle boundaries have been chosen at 10°. ~~Quartz~~ Qtz grain boundaries with 60°±5° of misorientation were disregarded from grain detection procedure, to avoid any contribution from Dauphiné twinning. ~~Plagioclase~~ 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 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 parameters (Halfwidth: 10°). Contouring lines are given only for the 0.5-10 m.u.d. (multiple of uniform distributions) range.

~~A.2 SEM – Cathodoluminescence~~

~~Cathodoluminescence 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 artifacts in the sample, secondary (SE) and backscatter electron images were collected simultaneously with CL.~~

A.2~~3~~ Grain size ~~and aAspect rRatio~~ 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 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 (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) was obtained interpolating distribution data with a 6th degree polynomial equation in Excel-MS Office. Relative frequencies are normalized to 1.

A.3~~4~~ Image analysis

Image analysis of grain shape was performed on both SEM-BSE images and phase maps obtained 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 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.

~~**A.5 Electron microprobe analysis (EMPA)**~~

~~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 (feldspar, epidote and phyllosilicate) beam current. PAP correction program was applied to convert X-ray counts into oxide weight percentages.~~

Author contributions

AC, LM~~,~~ and GP ~~and AC~~ 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 ~~performed~~ the rheological calculations. LFGM performed cathodoluminescence analysis. AC prepared the figures and the manuscript with contributions from all the co-authors.

Competing interests

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.

Figure 1. Microstructures of Rieserferner granodiorite mylonites. (a) Microphotograph (crossed ~~nichols~~polarizers) showing the ~~layered structure of granodiorite mylonites, composed of~~ alternating layers of recrystallized ~~quartz~~Qtz, of recrystallized ~~biotite~~Bt + ~~plagioclase~~ Plg + Qtz~~quartz~~, and of ~~plagioclase~~ Plg + Qtz~~quartz~~. White arrows indicate layers of recrystallized Qtz~~quartz~~ (upper) and Bt~~biotite~~ (lower). (b) SEM-BSE image of the area shown in (a). (c) SEM-BSE image of a pristine myrmekite (Myrm) replacing ~~K-feldspar~~Kfs. (d) SEM-BSE image of the ~~K-feldspar~~Kfs + ~~biotite~~Bt tails in strain shadows between two ~~plagioclase~~ Plg porphyroclasts. ~~K-feldspar~~Kfs in the strain shadows is in turn replaced by myrmekite (white arrows). (e) SEM-BSE image of a ~~K-feldspar~~Kfs porphyroclast and of sheared myrmekite. Pristine myrmekite developed on Kfs ~~K-feldspar~~ boundaries parallel to the mylonitic foliation are sheared to form ~~plagioclase~~ Plg + ~~quartz~~ Qtz aggregates (sheared myrmekite). The white polygon encloses ~~K-feldspar~~Kfs neoblasts in strain shadows and sheared myrmekite. (f) CL image of (e). Note the alteration of the CL signal in ~~quartz~~Qtz after the EBSD scan (area delimited by white dashed line). (g) ~~K-feldspar~~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) Mosaic of SEM-BSE images with the ~~K-feldspar~~Kfs and the myrmekite + sheared myrmekite coloured in red and pale blue, respectively. The yellow rectangles indicate the location of the EBSD maps of Figs. 3, 4, 5 and SOM2. (b) Bar diagram showing the volume ~~percentage~~ amount of ~~K-feldspar~~Kfs (red bars) and myrmekite (pale blue bars) across the microstructure: PM = protomylonite; M = mylonite; and- UM = ultramylonite.

Figure 3. EBSD map and crystallographic orientation data of incipient myrmekite and parent ~~K-feldspar~~Kfs. (a) EBSD-derived phase map. The area delimited by dashed polygons represents pristine myrmekite. Pole figures for: (b) ~~K-feldspar~~Kfs grains on which pristine myrmekite nucleated; (c) ~~plagioclase~~ Plg and (d) ~~quartz~~ Qtz in pristine myrmekite.

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 ~~quartz~~ Qtz from the sheared myrmekite of A~~a~~rea B. Upper

row: scattered data. Lower row: contoured data. (c) Misorientation axis distributions for Qtz ~~quartz~~ in sample (upper row) and crystal (lower row) coordinate system. (d) Misorientation angle distribution for Qtz~~quartz~~. (e) Pole figures for ~~plagioclase~~ Plg from sheared myrmekite of Area B. Upper row: scattered data. Lower row: contoured data. In this case, the [100] ~~plagioclase~~ Plg pole figure is reported in upper hemisphere, where the maximum has been observed. (f) Misorientation axis distributions for ~~plagioclase~~ Plg in sample (upper row) and crystal (lower row) coordinate system. (g) Misorientation angle distribution for ~~plagioclase~~Plg.

~~**Figure 5.** EBSD orientation maps for K-feldspar and plagioclase. (a) Orientation map for Kfs of Fig. 3.~~ (~~b~~h) Pole figures ~~reporting~~of the crystallographic orientation of Kfs porphyroclasts included in Areas C and E and respective tails. (~~c~~i) Misorientation axis distributions in sample (upper row) and crystal (lower roaw) coordinate system for porphyroclasts and tails. (~~d~~j) Pole figures ~~reporting~~of the crystallographic orientation of Kfs porphyroclast A and ~~fine-grained~~ Kfs ~~aggregate~~neoblasts in the strain shadow (Area D ~~Fig. 4~~). (~~e~~k) Misorientation axis distributions in sample (upper row) and crystal (lower row) coordinate system for ~~fine-grained~~ Kfs ~~aggregate~~neoblasts. (~~f~~l) Grain size distribution for the ~~fine-grained~~ Kfs ~~aggregate~~neoblasts.

Figure ~~6~~5. EBSD orientation data and mapping for pure Qtz ~~quartz~~ 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 ~~quartz~~ layer. (b) Pole figures for Qtz ~~quartz~~ [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~~quartz~~.

Figure ~~5~~76. Image analysis of ~~then~~ phase spatial distribution in myrmekite. The diagram reports phase- and grain-boundary fractions in pristine- and ~~for~~ sheared myrmekite. Continuous curves represent the theoretical probability of phase- and grain-boundary fraction as a function of Qtz ~~quartz~~ 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 ~~related plagioclase~~Plag grain boundaries, the ~~quartz~~ Qtz grain boundaries, and the Plag-Qtz phase boundaries.

Figure 8~~76~~. Area-weighted grain size distributions and SPO for ~~quartz~~Qtz. (a) Grain size distribution for Qtz ~~quartz~~ in incipient myrmekite A in Fig. 4a. (b) Grain size distribution for Qtz ~~quartz~~ in sheared myrmekite B in Fig. 4a. (c) Grain size distribution for Qtz ~~quartz~~ in sheared myrmekite C in Fig. 4a. (d) Grain size distribution for Qtz ~~quartz~~ in monomineralic layer in Fig. 4a. (e) Relative frequency distribution of grain aspect ratio for Qtz~~quartz~~. (f) Rose diagram showing the orientation of major axis of Qtz ~~quartz~~ grains, defining a weak SPO.

Figure 9~~7~~8. Area-weighted grain size distributions and SPO for ~~plagioclase~~Plg. (a) Grain size distribution for ~~plagioclase~~ Plg in myrmekite of Fig. 3. (b) Grain size distribution for ~~plagioclase~~ Plg in incipient myrmekite A in Fig. 4a. (c) Grain size distribution for ~~plagioclase~~ Plg in sheared myrmekite B in Fig. 4a. (d) Relative frequency distribution of grain aspect ratio for ~~plagioclase~~Plg. (e) Rose diagram showing the orientation of major axis of ~~plagioclase~~ Plg grains, defining a weak SPO.

Figure ~~10~~9~~8~~. Diagrams ~~obtained~~ derived from the calculation of the rheological model explained in the text. Grain~~s~~ size vs. ~~D~~differential stress map with contoured strain rate curves ~~obtained~~ calculated for: (a) ~~quartz~~Qtz, (b) 80% ~~plagioclase~~ Plg (An_{60}) + 20% ~~quartz~~ 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 ~~quartz~~ 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 ~~obtained~~ derived from piezometric calculations on pure ~~quartz~~ 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~~ differential stress vs. Log ~~Strain~~ strain rate diagram reporting the curve calculated for pure ~~quartz~~ Qtz with different grain sizes, 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~~ differential stress vs. Log ~~Strain~~ strain rate diagram reporting the curve calculated for pure ~~quartz~~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% ~~plagioclase~~ An_{60} Plg + 20% Qtz). Maximum ~~substitution~~ replacement is limited to 20% of initial feldspar (see text for explanation).