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 with~~use EBSD (i) to investigate the microstructure of a granodiorite mylonite, developed at ~~ca.~~ ~ 4~~20-460~~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 myrmekite~~sheared myrmekite – promoted grain size-sensitive creep mechanisms including fluid-assisted grain boundary sliding in plagioclase, coupled with heterogeneous nucleation of quartz within creep cavitation pores. Flow laws, calculated for monomineralic quartz, feldspar, and quartz + plagioclase aggregates (~~sheared myrmekite~~sheared myrmekite)~~,~~ during deformation at 450 °C, show that ~~during mylonitization at 450 °C~~ grain-size-sensitive creep in ~~sheared myrmekite~~sheared myrmekite accommodated strain rates several orders of magnitude higher than monomineralic quartz layers deforming by dislocation creep. Therefore, diffusion creep and grain size-sensitive processes contributed significantly to bulk rock weakening during mylonitization. Our results have implications for modelling the rheology of the felsic middle ~~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., 2015~~de 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~~ resulted~~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 extending~~ed~~ 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.~~

~~5~~4.1 Pristine myrmekite

~~Characteristics of p~~Pristine myrmekite ~~are~~shows: (i) ~~the~~ preferential development along grain boundaries of ~~K-feldspar~~Kfs 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-feldspar~~Kfs (Fig. 1c); (iii) ~~the monocrystalline~~ single grain structure of ~~plagioclase~~Plg within each lobe ~~(20 to 50 µm in size: Fig. 7a)~~, embedding vermicular ~~quartz~~Qtz ~~(sections up to 3 µm in equivalent size: Fig. 6a)~~; (iv) ~~the~~ rather constant spacing ~~between the~~of ~~quartz~~Qtz vermicules of about 3-5 µm across the entire lobe; and (v) ~~the~~ preferential elongation of the ~~quartz~~Qtz vermicules orthogonal to the myrmekite/~~K-feldspar~~Kfs boundary.

The EBSD analysis ~~of the crystallographic relationships between the K-feldspar and the replacing myrmekitic plagioclase and quartz~~ shows that: (i) ~~K-feldspar~~Kfs and myrmekitic ~~plagioclase~~Plg commonly ~~show~~ have similar crystallographic orientations ((100)$_{Kfs}$ || (~~{~~100)~~}~~$_{Plg}$, (010)$_{Kfs}$ || (010)$_{Plg}$, and (~~{~~001)~~}~~$_{Kfs}$ || (001)$_{Plg}$:~~;~~ Fig. 3b, c); (ii) ~~the~~ ~~quartz~~Qtz vermicules do not share any crystallographic plane or direction with ~~K-feldspar~~Kfs or myrmekitic ~~plagioclase~~Plg (Fig. 3b-c-d); (iii) ~~quartz~~Qtz 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 ~~quartz~~Qtz and ~~plagioclase~~Plg, respectively.

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

~~5~~4.2 Sheared myrmekite: plagioclase + quartz aggregates

~~Shearing of myrmekite gave rise to~~ ~~Pplagioclase~~Plg + ~~quartz~~Qtz aggregates (± rare ~~K-feldspar~~Kfs and ~~biotite~~Bt) wrap around ~~K-feldspar~~Kfs porphyroclasts and are elongate~~d~~ into the foliation (Fig. 1e). These aggregates ~~are directly connected to and depart~~make transition to, and extend into the foliation from, pristine myrmekite~~,~~ and are hereafter referred to ~~hereafter~~ as sheared myrmekite.

~~Quartz~~Qtz grains ~~of~~ in sheared myrmekite occur either as isolated single grains at triple/quadruple junctions ~~of~~between ~~plagioclase~~Plg 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). QuartzQtz 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). PlagioclasePlg 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 plagioclasePlg and quartzQtz have a CL grey shade similar to the surrounding non-myrmekitic plagioclasePlg and quartzQtz (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-feldsparKfs neoblasts occur in strain shadows around feldspar porphyroclasts, as well as dispersed within the sheared myrmekite (Figs. 3a, Area C in Fig. 4a; SOM2a5a; 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. SOM24h-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-feldsparIn particular, the K-feldsparKfs neoblasts aggregate shows 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. SOM2e4k5e).

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 ~~9~~8~~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. ~~8~~7~~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 myrmekite~~s~~ 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. 76~~5~~) (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-feldspar~~Kfs ($Or_{96}Ab_{4}$) (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 sliding~~GBS/rigid body rotation~~ during myrmekite shearing (Behrmann and Mainprice, 1987; Menegon et al., 2008, 2013).

7~~6~~.2.3. Monomineralic quartz layers

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

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 ~~quartz~~Qtz microstructure during a prolonged deformation history or, more likely, the development of the microstructures at different temperature conditions during pluton cooling. The bimodal grain size of recrystallized ~~quartz~~Qtz includes coarser grains that we infer developed during the relatively high-temperature bulk solid-state deformation of the host granodiorite predating the development of localized shear zones at 450 °C dominated by SGR recrystallization (Ceccato et al., 2017; Ceccato and Pennacchioni, 2018). Coarser grains in ~~quartz~~Qtz 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).

7~~6~~.3. The rheology of the Rieserferner mylonites

The rheological effect of transformation of coarse ~~K-feldspar~~Kfs to fine-grained sheared myrmekite and the transition to an interconnected, weak, fine~~-~~grained microstructure (Handy, 1990) is estimated here by investigating the deformational behaviour of different mixtures of ~~plagioclase~~Plg and ~~quartz~~Qtz, in which deformation is accommodated either ~~deforming~~ ~~via~~by ~~different contribution of~~ dislocation ~~-~~creep ~~creep~~ ~~and~~or by diffusion creep. Our simplified model does not include ~~biotite~~Bt, white micaWmca and biotiteBt + plagioclasePlg aggregates. Based on the deformation mechanisms that we identified from ourOur 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. 1098):

(i) monomineralic quartzQtz layer deforming via both dislocation and diffusion creep (Fig. 1098a);

(ii) sheared myrmekite, modelled as 80 vol% plagioclasePlg (An_{60}) + 20 vol% quartzQtz deforming via both dislocation creep and grain size sensitive creep (Fig. 1098b); the input grain size is 7 µm, identical for both minerals;

(iii) a mixture of 60% plagioclasePlg (An_{100}) + 40% quartzQtz assumed as a simplified composition representative of a mica-free granitoid rock deforming only by dislocation creep (after referred as "granitoid") (Fig.1098c).

The flow law of Hirth et al. (2001) has been adoptedused 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) $\dot{\varepsilon}_{qps} = C_2 \frac{\rho_f}{\rho_s} \frac{\sigma}{d^3} \frac{V c D_w}{RT}$

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 ($\mu m^3\ mol^{-1}$); 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 ($\mu m^2\ s^{-1}$). 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:

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

where: $\dot{\varepsilon}_{Disl}$ 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:

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

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:

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

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

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

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

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}).

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

;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) $\mathrm{Log}_{10}\, n_a = \phi_1 \log_{10} n_1 + \phi_2 \log_{10} n_2$

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

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

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:

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

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:

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

where

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

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

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

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:

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

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

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

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

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

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 ~~T~~the differential stress of 40-70 MPa, estimated from the finer grain size of ~~quartz~~Qtz (20-35 µm), is~~ can be considered~~ representative of the bulk flow stress of the mylonite, the ~~quartz~~Qtz aggregates deforming by dislocation creep (Fig. 9~~10~~~~8~~a) would flow at~~. At constant stress conditions, such differential stress corresponds to~~ a strain rate of 10^{-11}-10^{-13} s^{-1} whereas~~of 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. ~~10~~9~~8~~b). 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. ~~10~~9~~8~~b). Therefore, assuming constant differential stress conditions, a strain-rate partitioning of 2-4 orders of magnitude is expected between monomineralic ~~quartz~~Qtz and sheared myrmekite (similarly to Behrmann and Mainprice, 1987). Such strain-rate partitioning ~~at constant stress~~ could also explain the observed decrease in ~~quartz~~Qtz grain size from the core of monomineralic layers toward neighbouring sheared myrmekite (Fig. 4).

Assuming constant strain rate conditions of 10^{-11} - 10^{-12} s^{-1}, t~~T~~he 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 ~~quartz~~Qtz and sheared myrmekite is not quantifiable; however, the sheared myrmekite are always weaker than monomineralic ~~quartz~~Qtz 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. ~~10~~9~~8~~b).

7~~6~~.3.2. The effect of myrmekite reaction

Figure ~~9d~~ ~~10~~9d shows the different curves describing the rheological behaviour of a simplified granitoid rock where ~~K-feldspar~~Kfs is progressively replaced, up to 20 vol%, by sheared myrmekite. The flow behaviour of the derived granitoid mylonite is represented by the grey curves, and is linear viscous for most of the investigated conditions. The complete consumption of ~~K-feldspar~~Kfs 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~~ioned~~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 <1µm^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.

Acknowledgements

Elena A. Miranda and an ~~A~~anonymous reviewer are warmly thanked for their comments and reviews. Simone Papa, Francesco Giuntoli, Luca Pellegrino are thanked for fruitful discussions. Andrea Risplendente is thanked for his help during EMPA data collection at the Università degli Studi di Milano. The staff at University of Plymouth Electron Microscopy Centre is thanked for the assistance during EBSD data acquisition. Luca Menegon acknowledges the financial support from a FP7 Marie Curie Career Integration Grant (grant agreement PCIG13-GA-2013-618289). Financial support from the University of Padova ("Progetto di Ateneo" CPDA140255) and from the Foundation "Ing. Aldo Gini" is acknowledged.

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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 ro~~a~~w) 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 ~~the~~n ~~-~~ 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 87~~6~~. 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 978. 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 1098. 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).