Dear Florian,

Thank you very much for the editorial handling and your additional comments!

We agree that there is good reason to separate instantaneous from finite strain ellipsoids, if the rocks record information about it. The mylonitic pegmatites show a foliation and stretching lineation, characterized by large fragmented magmatic tourmaline and feldspar porphyroclasts and alternating quartz-, albite- and mica-rich layers. The plane normal to the sample-scale foliation and stretching lineation are interpreted to indicate the principal axes of the finite strain ellipsoid *Z* and *X*, respectively (as stated in the revised manuscript beginning of chapter 4 p. 6, line 9, 10). The foliation can be deflected around larger porphyroclasts. In rare cases, strain shadows are asymmetric (Fig. 4) and few shear bands are present (Fig. 12 a, b). The scale that we are addressing when we discuss the development of the microstructure is the sample scale. We do not intend to discuss the relative contributions of pure shear / simple shear / co-axial / non-coaxial deformation or any kinematics on a larger scale, which is beyond the scope of this study. We changed our wording throughout the manuscript and refer to the observed sample-scale foliation and stretching lineation, as this is the objective observation.

In the submitted final manuscript we made the following changes:

At the beginning of chapter 4 we rephrased to: ”The plane normal to the observed foliation and the stretching lineation on sample-scale are interpreted to represent the principal axes of the finite strain ellipsoid *Z* and *X*, respectively, which are indicated in micrographs.”

In the captions to Fig. 2b, Fig. 5a, b, Fig. 13 we now also refer to the observed stretching lineation / foliation (as opposed to referring to a “shortening direction”, which we used in the sense of the plane normal to the observed foliation on sample scale, but we understand that this wording is misleading).

We omitted p9, l2-3. (“The porosities parallel to the short axes of grains, the elongate shape and the zoning indicate that grains grew at boundaries perpendicular to the stretching lineation”.)

A few additions to the specific comments of Ruedigers review:

21) Fig. 13: “Preferred growth parallel to stretching lineation” Why would it grow parallel to the finite stretching direction - unless the pure shear p.d. contribution is very large shouldn’t it grow parallel to the extending ISA and eventually rotate? All figures, where a shear sense is available but not provided, should have nice arrows indicating the shear sense.

It is true that a grain would not necessarily grow parallel to the finite stretching direction, but likely that it grows parallel to the extending ISA. In our samples the long axis of most matrix grains is within the foliation. Whether any rotation relative to a microstructure on sample scale or larger scale was involved is not recorded.

In Fig. 13 we did not refer to "preferred growth parallel to the stretching lineation” therefore we assumed that Ruediger was referring to Fig. 14, where we rephrased that statement accordingly. As indeed the phrase “preferred” might have been misleading (see also point 46) we rephrased this throughout the revised manuscript.

The microstructures shown in the SE-images of Fig. 13 do not indicate a shear sense.

30) p7, l2: LAB parallel to shortening direction: where is the shortening direction?

We rephrased that sentence in the revised manuscript to:

"Low-angle boundaries are typically observed oriented at high angle to the stretching lineation, indicating that they represent healed cracks associated with a slight misorientation rather than indicating subgrains (Fig. 8a)."

46) p11. l27: growth parallel to the stretching lineation: While this does not make a lot of sense for non-coaxial p.d. (see comment 2), why preferred growth? Preferred by what? Crystallography? Where should the "dilation" come from? Anything tested on that? What is the CPO of the most elongated grains, or which crystal direction is parallel to the maximum grain elongation direction?

The paragraph 5.5 has been rewritten in the revised manuscript, such that the sentence, Ruediger was referring to in the original manuscript, is not present anymore.

The phrase "preferred" might have been misleading (see also point 21) and we rephrased this throughout the revised manuscript. We did not refer to a crystallographic preferred growth but formation of growth rims causing a SPO (not CPO) with the long axes of grains within the foliation plane. The observation is: The long axes of grains is within the foliation plane. There is no preferred crystallographic orientation of grains with high aspect ratio (see also comments to points 21 and 28).

To the comments on "extension / dilation" we answered at point 28 the following: During dissolution-precipitation creep, boundaries at high angle to the extensional direction are "sites", where new material is precipitated for example in veins or strain shadows, causing dilation/extension in this specific direction. Throughout the revised manuscript, we used the term "strain shadow" to refer to these areas.

We hope that our manuscript is now acceptable for publication in Solid Earth.

Thank you and with best regards,

Felix Hentschel

Deformation of feldspar at greenschist facies conditions – the record of mylonitic pegmatites from the Pfunderer Mountains, Eastern Alps

Felix Hentschel, Claudia A. Trepmann, Emilie Janots

Abstract

Deformation microstructures of albitic plagioclase and K-feldspar were investigated in mylonitic pegmatites from the Austroalpine basement south of the western Tauern Window by polarized light microscopy, electron microscopy and electron backscatter diffraction to evaluate ~~the rheologically dominant~~ feldspar deformation mechanisms at greenschist facies conditions. The main mylonitic characteristics are alternating almost monophase quartz and albite layers, surrounding porphyroclasts of deformed feldspar and tourmaline. The dominant deformation microstructures of K-feldspar porphyroclasts are intragranular fractures ~~parallel to the main shortening direction indicated by the foliation.~~at high angle to the stretching lineation. The fractures are healed or sealed by polyphase aggregates of albite, K-feldspar, quartz and mica, which also occur along intragranular fractures of tourmaline and strain shadows around other porphyroclasts. ~~Polyphase~~These polyphase aggregates~~ at sites of dilation~~ indicate dissolution-precipitation creep. K-feldspar porphyroclasts are partly replaced by albite characterized by a ~~sawtooth-shaped~~cuspate interface. This replacement is interpreted to ~~be~~take place by interface-coupled dissolution-precipitation driven by a solubility difference between K-feldspar and albite~~ and is not controlled by strain. In contrast, albite~~. Albite porphyroclasts are replaced at ~~sites of shortening~~boundaries parallel to the foliation by fine-grained monophase albite aggregates of small strain-free new grains mixed with deformed fragments. Dislocation glide is indicated by bent~~, kinked~~ and twinned albite~~. No~~ porphyroclasts with internal misorientation. An indication of effective dislocation climb with dynamic recovery, for example by the presence of subgrains, ~~a crystallographic preferred orientation or sutured grain boundaries was observed.~~is systematically missing. We interpret the grain size reduction of albite ~~at sites of~~

Commented [F1]: Point 1, review #2

Commented [F2]: Point 1, review#1

Commented [F3]: Point 3, review#1

~~shortening~~ to be the result of coupled ~~fracturing,~~ dislocation glide and fracturing (low-temperature plasticity). Subsequent growth is by a combination of strain-induced grain boundary migration~~.~~ and formation of growth rims resulting in an aspect ratio of albite with the long axis within the foliation. This strain-induced replacement by nucleation ~~and growth leads,~~(associated dislocation glide and microfracturing) and subsequent growth is suggested to result in the observed monophase albite layers, probably together with granular flow~~, to the monophase albite layers.~~. The associated quartz layers ~~in contrast~~, show characteristics of dislocation creep by the presence of subgrains, undulatory extinction and sutured grain boundaries. We identified two endmember matrix microstructures ~~that correlate with strain. Samples with lower strain are characterized by layers of~~ :(i) alternating layers of a few hundreds of µm width, with ~~coarse-grained quartz and layers with~~ isometric, fine-grained feldspar~~. Higher strained samples are characterized by narrow alternating layers of~~ (in average 15 µm in diameter) and coarse-grained quartz (a few hundreds of µm in diameter), representing lower strain compared to (ii) alternating thin layers of some tens of µm width composed of fine-grained quartz (< 20 µm in diameter) and coarse elongate albite grains ~~elongated parallel to~~ (long axis a few tens of µm) defining the ~~stretching lineation~~foliation, respectively. ~~These~~ Our observations indicate that grain size reduction by strain-induced replacement of albite~~,~~ (associated dislocation glide and microfracturing) followed by growth and granular flow ~~assisted by fracturing and dissolution-precipitation together~~simultaneous with dislocation creep of quartz are ~~rheologically dominant~~playing the dominating role in formation of the mylonitic microstructure.

Commented [F4]: Point 7, review #2

1. Introduction

Assessment of the rheological behaviour of the continental crust requires an understanding of grain-scale deformation mechanisms of the main rock-forming minerals at not directly accessible depths. In deep parts of seismically active shear zones (10-20 km) the rheological behaviour is controlled by the deformation of granitoid rocks, mainly composed of feldspar and quartz, at greenschist facies conditions. A vast number of experimental studies exist to analyse the deformation mechanisms and to derive flow laws for high-temperature creep of feldspar (e.g. Gleason and Tullis, 1993; Kruse and Stünitz, 1999; McLaren and Pryer, 2001; Stünitz et al., 2003; Rybacki and Dresen, 2004) and quartz (e.g., Jaoul et al., 1984; Patterson and Luan, 1990; Gleason and Tullis, 1993; Hirth et al., 2001). However, the extrapolation of experimentally deduced flow laws for monomineralic material to the flow behaviour of polymineralic rocks at geologically reasonable conditions is problematic (e.g., Pfiffner and Ramsay, 1982; Tullis and Tullis, 1986; Paterson, 1987; Jordan, 1988). Also, the application of flow laws to model the rheological properties of the continental lithosphere (e.g. Brace and Kohlstedt, 1980; Kohlstedt et al., 1995) is a matter of debate (e.g., Rutter and Brodie, 1991; Burov, 2007; Bürgmann and Dresen, 2008; Burov, 2011). Uncertainties in models for the rheological properties of the continental lithosphere is partly due to a poor knowledge of the deformation mechanisms actually proceeding at depth as well as the interplay between multiple factors influencing rock strength such as stress variations, fluid content, and metamorphic reactions. The comparison of experimental results with microstructural and mineralogical observations of exhumed metamorphic granitoid rocks, which record the grain-scale mechanical and chemical transformations at depths, is therefore indispensable.

The extrapolation of experimental flow laws for dislocation creep of quartz to natural conditions is found to agree well to natural observations (e.g., Stöckhert et al., 1999, Hirth et al., 2001, Stipp et al., 2002). However, there are large discrepancies in experimental and natural observations on the most abundant mineral of the continental crust, feldspar. Deformation experiments suggest that dislocation creep of feldspar in high strain shear zones is dominant only at high temperatures above about 900°C (e.g., Rybacki and Dresen, 2004). In contrast, ductile deformation with grain-size reduction and formation of new feldspar grains, commonly assumed to imply dislocation creep, is observed already at greenschist facies conditions (Voll, 1976; Tullis, 1983; Gapais, 1989; Stünitz, 1993; Prior and Wheeler, 1999; Ishii et al., 2007). This discrepancy is partly due to the unclear and strongly varying contribution of brittle, dissolution-precipitation and crystal-plastic processes (e.g., Tullis and Yund, 1987; Fitz Gerald and Stünitz, 1993; Stünitz and Fitz Gerald, 1993; Tullis et al., 1996; Prior and Wheeler, 1999; Kruse and Stünitz, 2001; Ree et al., 2005; Menegon et al., 2006, 2008; Stünitz et al., 2003; Mehl and Hirth, 2008; Sinha, et al., 2010; Kilian et al., 2011; Brander et al., 2012; Mukai et al., 2014; Eberlei et al., 2014). Such a creep behaviour governed by the interaction of different deformation mechanisms and chemical reactions in the presence of fluids is especially difficult to assess in experimental approaches. This is partly because experiments have to be performed at high temperatures to realize feasible strain rates, which, however, affects phase assemblages and material properties, for example by partial melting. Therefore, activated mechanisms may strongly differ from those at natural strain rates and greenschist facies conditions. Tullis and Yund (1987) found in their deformation experiments at strain rates of 10^{-4} s^{-1} to 10^{-6} s^{-1} effective dislocation climb with subgrain formation and subgrain rotation only effective at temperatures >900°C. They concluded that optically visible subgrains in feldspar from low-grade rocks should not directly be assumed to arise from crystal plasticity but may arise from cataclasis and subsequent healing. Dislocation climb necessary for dynamic recovery and recrystallization requires intracrystalline diffusion. At temperatures <550°C, the NaSi ↔ CaAl interdiffusion rates for plagioclase are very low (Yund, 1986; Korolyuk and Lepezin, 2009). In the presence of water, the diffusion coefficient has been interpreted to be higher (Yund, 1986), which was suggested to account for the weakening observed in experiments where fluid is present (e.g. Rybacki and Dresen, 2004). TEM studies also show that sufficient dislocation climb to produce subgrains iseffective only at temperatures from the middle amphibolite upward (e.g. White, 1975; Stünitz et al., 2003). ~~However, whether an~~The experiments by Tullis and Yund (1985) show that grain boundaries may migrate into areas of higher dislocation density introduced by microfracturing driven by the reduction in strain energy (Tullis and Yund, 1987) at conditions, at which recovery is not active. However, whether extrapolation to natural conditions is valid can only be evaluated by a comparison to natural microstructures.

Commented [F5]: Points 34-36, review #2

To analyse the deformation behaviour of feldspar at greenschist facies conditions, we use in this study the record of mylonitic pegmatites of the Austroalpine basement south of the western Tauern Window and north of the Periadriatic line (Fig. 1). They show a wide range of feldspar deformation microstructures and are compositionally and mineralogically relatively simple, as they are characterized by a Ca-poor bulk-rock composition (Stöckhert, 1987). ~~We distinguish specific feldspar microstructures that represent the replacement of large deformed feldspar porphyroclasts in mylonitic pegmatites driven by stored strain energy and chemical disequilibrium and which in combination with fracturing, dislocation glide, grain boundary migration and dissolution-precipitation creep form specific types of feldspar-quartz matrix microstructures. The aim is to detect specific microstructures that can be related to processes that govern the rheological behaviour of the rocks.~~ The goal of this study is to correlate characteristic microstructures to specific processes responsible for their formation and to discuss the rheological behaviour of the rocks based on our findings.

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Commented [F7]: Point 1, review#2

2. Geological ~~Setting~~setting and ~~Sampling~~sampling

The pegmatites occur within high-grade polymetamorphic upper Austroalpine basement rocks located between the western Tauern window in the north and the Defereggger-Antholz-Valser (DAV) shear zone in the south (Fig. 1~~, ~~;e.g~~.,~~. Hoffmann et al., 1983; Stöckhert, 1987; Stöckhert et al., 1999; Mancktelow et al., 2001; Schmid et al., 2004; Müller et al., 2000). Pegmatite crystallization age is generally assumed to be Permian (262 ± 7 Ma, Borsi et al. 1980) consistent with other pegmatite occurrences in the Austroalpine basement (e.g., Habler et al., 2009; Thöni and Miller, 2009). The pegmatites are characterized by a Ca-poor composition originated from water-rich anatectic melts (Stöckhert, 1987, Schuster ~~&~~and Stüwe, 2008).

Commented [F8]: Point 4, review#1

The intrusion of the Rensen and Rieserferner tonalites and related magmatic dikes into the Austroalpine basement rocks took place at ca. 30 Ma (Borsi et al., 1978; 1979; Steenken et al., 2000). ~~The DAV shear zone was active at about the same time~~The amount of uplift and erosion since the intrusion of these magmatic bodies is increasing from about 10 km in an eastern area of the Rieserferner to about 15 to 25 km in the Rensen area in the west (Trepmann et al., 2004). The main activity of the DAV shear zone was at about the same time as the magmatic intrusions and is characterized by an oblique strike slip movement with some tens of kilometres of horizontal component (sinistral sense of shear) and a few kilometres of vertical component, where the northern part of the Austroalpine basement is uplifted relative to the southern part (Borsi et al., 1978; Kleinschrodt, 1987; Schulz, 1989; Ratschbacher et al., 1991; Stöckhert et al., 1999; Mancktelow et al., 2001). It is accompanied by smaller sinistral shear zones to the north, some of which were already active in the Eocene (Mancktelow et al., 2001). The DAV shear zone is viewed as part of the Southern limit of Alpine Metamorphism (SAM) as defined by Hoinkes et al. (1999). To the north of the DAV shear zone, tertiary ages for several mineral systems are widespread (Mancktelow et al., 2001; Schulz et al., 2008) and the metamorphic conditions are constrained to 450±50 °C and pressures of about 0.7 GPa by phase relations in the metapelitic Austroalpine basement rocks (Stöckhert 1982; 1987; Schulz et al., 2008; unpubl. data). ~~Additionally, the northern part shows an increase in exhumation depth towards the west (Trepmann et al., 2004).~~ South to the DAV shear zone, the Austroalpine basement rocks have been solely affected by minor metamorphism associated with brittle deformation, in accord with no resetting of the Rb/Sr biotite Permian ages of 288-299 Ma (Borsi et al., 1978; Stöckhert, 1982; Kleinschrodt, 1987; Schulz, 1994).

The association of the deformation microstructures recorded by the pegmatites ~~with the~~withthe Alpine history is discussed controversially (e.g., Mancktelow et al., 2001; Schulz et al., 2008). Stöckhert (1982, 1984, 1987) proposed that the annealed quartz and feldspar microstructures in the mylonitic pegmatites correlate to an early Alpine deformation stage at metamorphic temperatures of 450±50 °C, pressures of about 0.7 GPa and at about 100 Ma (white mica K-Ar data, Stöckhert, 1984). This age corresponds to the Eoalpine (Cretaceous) tectonometamorphic event recorded from other units of the Eastern Austroalpine basement (e.g. Thöni and Miller, 1996; Habler et al., 2009). A later (Oligocene) deformation stage at 300 to 350°C was proposed by heterogeneous high-stress quartz microstructures in quartz-rich lithologies of Austroalpine basement rocks related to the movement along the DAV shear zone (Stöckhert, 1982, 1984; Kleinschrodt, 1987; Stöckhert et al., 1999). Mancktelow et al~~. (~~.(2001), however, argued, based on microstructural and kinematic studies, that the deformation microstructure of feldspar could also be Paleogene in age and they find no clear distinction between separate low- and high-T events.

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We sampled about 100 pegmatites in three field campaigns in 2015 and 2016. Their appearance varies mostly between m- to cm-sized veins or lenses~~,~~, and occasionally km-sized bodies occur (Stöckhert, 1987, Hofmann et al., 1983). In a few cases a ~~mineralogical~~ mineral zoning is present. ~~Pegmatites~~Deformed pegmatites, in veins or layers, have a foliation, which is parallel to that of the host gneisses. The largest pegmatite bodies appear macroscopically undeformed. We selected pegmatites with a pronounced foliation and stretching lineation (Fig. 2a; Appendix 1, Table 1). There is no apparent systematic variation in strain with distance to the DAV shear zone~~.~~, yet the distribution of different matrix microstructures, as described and discussed in sections 4.4. and 5.5., is different from west to east (Fig. 1).

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3. Methods

Samples were cut perpendicular to the foliation and parallel to the stretching lineation. Thin sections of ~30 µm thickness were first polished mechanically and then chemo-mechanically in a colloidal silica-solution. For scanning electron microscopy (SEM) thin sections were coated with a thin layer (~5 nm) of carbon. Electron microscopic investigations were performed on a Hitachi SU5000 with a field emission gun. Semi-quantitative chemical measurements by energy dispersive spectroscopy (EDS, AzTec, Oxford instruments) were acquired using an accelerating voltage of 20 kV and a working distance of 10 mm. Cathodoluminescence (CL) imaging using a Gatan MiniCL detector was performed at 5 kV and 10 mm working distance.

Crystallographic orientations were analysed using a HKL NordlysNano high-sensitivity Electron Backscatter Diffraction (EBSD) detector~~-~~(Oxford Instruments). The EBSD signals were acquired using the AzTec analysis software (Oxford instruments). We used a sample holder pre-tilted at 70° with respect to the electron beam, an accelerating voltage of 20 kV and a working distance of 20~~-~~ - 25 mm. The step size for automatic mapping was in the range of 1-2 µm, dependent of the required resolution, grain size and size of the area measured.

~~Pole figures were calculated using HKL Channel 5 software (Oxford instruments) and the MTEX software (Bachmann et al., 2010) from the raw EBSD output. The latter software was used to colour EBSD maps and for misorientation analysis. For grain reconstruction a thresholding value of 10° was used.~~EBSD data were analysed with the MTEX toolbox for Matlab, developed by Ralf Hielscher (https://mtex-toolbox.github.io/; e.g. Bachmann et al., 2010). Small non-indexed pixels were filled during data smoothing by a half-quadratic filter (Bergmann et al., 2015). For grain reconstruction a thresholding value of 10° was used. For grain reconstruction, Dauphiné twin boundaries in quartz are neglected by merging grains along boundaries characterized by a misorientation angle of 60° and a [0001] rotation axis. Evaluating albite grain boundaries in full misorientation space (Krakow et al., 2017) revealed that almost all twins correspond to the albite law and some to the pericline law. For grain reconstruction of albite, grains were merged along the corresponding twin boundaries. Evaluating mean grain orientations neglecting the twin orientations requires the use of a higher symmetry, which contains the symmetry element responsible for twinning, which is the point group 121 for albite and 622 for quartz. The mean orientation of the “higher symmetry” grain is the modal orientation of the “lower symmetry” grain. Using the higher symmetry yields the same grain reconstruction result as merging along twin boundaries. Grain size analysis was by area normalization excluding border grains. The mean and median of the area distribution are given in histograms. The aspect ratio and the trend of the grain long axis were calculated from an area-equivalent best-fit ellipse. Pole figures were calculated either from the de-noised EBSD-data (scatter plots) or from orientation distribution functions (ODFs). ODFs were calculated from the grain mean orientation or from every pixel. For the calculation a “de la Vallée-Poussin” kernel was used (https://mtex-toolbox.github.io/; e.g. Bachmann et al., 2010). Kernel width was estimated with the Kullback–Leibler crossvalidation function of MTEX (https://mtex-toolbox.github.io/; e.g. Bachmann et al., 2010). Pole figure densities (pfJ; L2-norm of the pole figures) and texture index (TI, L2-norm of the ODF) are used to characterize texture strength (Mainprice et al., 2015).

For qualitative comparison, we choose to display poles to the (100), (010) and (001) planes in upper hemisphere pole figures for albite. The internal misorientation within grains is dependent on the density of geometrically necessary dislocations and thus is commonly used as a measure of ~~the~~ crystal-plastic strain (e.g. Nicolas and Poirier, 1976; Poirier, 1985; Wheeler et al., 2009). To compare the intragranular misorientation between grains, we used the grain kernel average misorientation (gKAM) (Kilian, 2017), which can be computed in MTEX. The kernel average misorientation is the misorientation angle averaged over a certain kernel width for every measured point. We used a kernel size of 24 pixels (3rd order neighbours) and ignored misorientation angles above 8~~°, because these are not resulting from low-angle grain boundaries or healed cracks and are thus not related to internal misorientation.~~°. The sum of these misorientation angles divided by the number of measurements in a grain is gKAM.

Commented [F13]: Points 9, review #1; Points 6, 8, review#2

Compositions of feldspars and other major minerals were measured by a Cameca SX100 electron microprobe, using 15 kV voltage, 10 nA beam current and 1 µm spot size. The ZAF correction scheme provided by Cameca was used.

4. Results

The primary magmatic assemblage of the pegmatite comprises quartz, albite-rich plagioclase, K-feldspar and muscovite with accessory tourmaline, garnet, zircon, apatite and monazite. The foliation and stretching lineation are characterized by large fragmented magmatic tourmaline and feldspar, here referred to as porphyroclasts~~, with their fragments separated parallel to the stretching lineation (Fig. 2a)~~ and alternating quartz-, albite- and mica-rich layers ~~deflected around the porphyroclasts~~ (Fig. ~~2b~~2a-d). ~~Feldspar in~~The plane normal to the ~~mylonitic~~ foliation ~~is 90-95 % albite, independent~~and the stretching lineation are taken as the principal axes of the ~~albite/K-feldspar porphyroclast ratio.~~finite strain ellipsoid ***z*** and ***x***, respectively, which are indicated in micrographs. The K-feldspar is Na-poor (<10%) and ~~shows only~~ rarely shows perthitic exsolution. Plagioclase porphyroclasts have a narrow compositional range of Ab_{96-100}. In few samples magmatic plagioclase with Ab_{95-86} ~~occurs, then~~ is present and in these grains zoisite inclusions are common. Magmatic garnet is Mn-rich and low in Ca (on average $Alm_{70}Gro_{4}Sp_{26}$). During metamorphism, garnet with a higher Ca- and lower Fe-component ($Alm_{35}Gro_{45}Sp_{20}$) partly replaced magmatic grains (Fig. 3a). Epidote and Fe-bearing phengitic white-mica (2 wt% FeO) grew in the foliation plane of mylonitic pegmatites (Fig. 3b). The Fe-bearing phengite sometimes directly replaces magmatic white mica. The modal percentage of albite and K-feldspar varies in the different samples: albite comprises about 60-40 % and K-feldspar about 5-30%. The matrix layers comprise about 95% albite, independent on the ratio of K-feldspar to albite porphyroclasts, which varies from 8:1 to 1:9. This observation is consistent with whole-rock compositions with a marked variation of Na_2O and K_2O reported by Stöckhert (1987). ~~In contrast all samples~~ Samples show homogenously low CaO (<1 wt.%) and FeO, MgO, MnO (< 1 wt.%) contents (Stöckhert,1987). The variations in the whole-rock composition were interpreted to be due to different compositions of the anatectic melt or mineral zoning in the pegmatite body and ~~influenced~~affected by external fluids (Stöckhert,

Commented [F14]: Points 2, 10, 28, 30, 40, 46, review #2

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1987). In the following, we describe the specific feldspar porphyroclast and matrix microstructures.

4.1. Strain shadows

In all samples, polyphase aggregates of K-feldspar, albite, quartz and mica occur in ~~areas of dilation~~prismatic strain shadows between tourmaline and feldspar fragments and surrounding feldspar porphyroclasts (Fig. 2b, Fig. 4a, b). Asymmetric strain shadows are characterized by different microstructures displayed in Figure 4a-c: polyphase aggregates of albite, K-feldspar and quartz characterize the upper-left and lower-right quadrants, whereas the lower-left and upper right quadrants contain almost monophase albite aggregates that alternate with quartz layers. This asymmetric strain shadow is indicating a sinistral sense of shear, with the polyphase aggregate representing ~~sites of dilation~~extensional quadrants and the monophase aggregate ~~sites of compression~~compressional quadrants. The shape of the albite grains in the monophase layers is rather elliptical with a long axis parallel to the layer, whereas the shape of the albite and K-feldspar grains in the polyphase aggregates are irregular ~~but~~and rather isometric. Grain sizes vary with long axes between 2 and 150 µm, the average of grain diameters is at ~~25 µm~~25µm (1σ = 19 µm) (Fig. 4h, i). The plagioclase composition uniformly ranges between Ab$_{97-100}$. ~~The~~ EBSD measurements of albite in strain shadows were analysed comparing single grain orientations with that of the host, comparing pole figures of scattered measurements as well as density plots recalculated from ODF (Fig. 4d-g). The EBSD data reveal ~~that there are neither~~no obvious orientation ~~relationships~~relationship between ~~the~~ new grains within aggregates ~~nor~~or a specific relationship between new grains and porphyroclasts~~ (Fig. 4c-g).~~, although some new grain orientations might correlate with that of the clast (compare to Fig. 4 f). Generally, the internal misorientation angles of the grains in aggregates with a typical diameter of 25-~~30 µm~~30µm is low with a maximum internal misorientation generally lower than 5°. The relative misorientation within the albite porphyroclast is lower than 10° (Fig. 4 c).

Commented [F19]: Points 2, 10, 28, 30, 40, 46 review# 2

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4.2. K-feldspar porphyroclasts

Single fractures in K-feldspar porphyroclasts are sealed by aggregates of K-feldspar, albite and quartz, representing prismatic strain shadows (Figs. 2b, 5c, d). Dispersed fluid inclusion trails at ~~low~~high angle to the ~~shortening direction~~stretching lineation are interpreted as healed microcracks (Figs. 5a-c). Areas comprising a high amount of healed microcracks are associated to undulous extinction, consistent with a bending of the crystal (Fig. 5a). This bending can be quantified by a change in misorientation angle of about 20° over a distance of 700 µm. Yet, in K-feldspar porphyroclasts that do not show dispersed healed microcracks, the internal misorientation angle within one grain is generally below 5° (Fig. 5d) over a grain size of several mm. The K-feldspar porphyroclast interface with new albite grains is ~~„saw tooth“-shaped,~~cuspate due to protrusions of small albite grains ~~through~~ into K-Feldspar over a length of a few tens of µm. Albite protrusions often have ~~curved~~ lobate grain ~~boundaries at~~boundariesat contact with K-feldspar porphyroclast (Fig. 6). The occurrence of this ~~sawtooth-shaped~~cuspate boundary is independent on position with respect to the stretching lineation or ~~shortening directions~~foliation (Fig. 5, 6). EBSD analysis reveals that there is no crystallographic relationship between K-feldspar porphyroclast and new albite grains and the misorientation angle to the porphyroclast is generally high (Fig. 5d, e). ~~-~~The new albite grains often contain numerous pores and inclusions of tiny (< 5 µm) apatite needles, at the vicinity of the K-feldspar porphyroclast interface (Fig. 6b, d). ~~Albite grains along~~The apatite inclusions are in some places also present in the ~~sawtooth-shaped boundaries cut off the healed~~K-feldspar (Fig. 6b, arrows). Healed microcracks terminate at new albite grains, which therefore are interpreted to have formed after fracturing (arrows in Fig. 5c, d).

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Commented [F23]: Point 19, review#1

Commented [F24]: Point 28, review #1

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4.3. Albite porphyroclasts

Albite porphyroclasts are commonly twinned, ~~kinked~~bent and fragmented (Fig. ~~7). Albite twins are often bent (Figs.~~ 7, 8). The deformed fragments are surrounded by a fine-grained albite ~~aggregates~~ aggregate (grain diameters of 27 µm in average) with a very similar composition (Ab_{96-100}) compared to the host albite, yet with a tendency to a somewhat higher albite component (< 1% higher Ab component). An irregular, patchy An-rich seam (up to An_{20}) is commonly observed around new albite grains (Fig. 7f). ~~The new~~New albite grains occur along fractures ~~and kinks~~ of deformed porphyroclasts that are oriented subparallel to the foliation, i.e., ~~at~~along sites of ~~shortening and~~ high strain and along boundaries parallel to the foliation (Fig. 7a-c, e). The new albite grains are typically not twinned, in contrast to fragments of the host (Fig. 7b, d). Larger host fragments have a relative high internal misorientation with angles typically of about 10° along a profile length of 100 µm, ignoring ~~twinning~~twin domains (Fig. 8g, h). Grain kernel average misorientation (gKAM) values (0.4-0.7 °) for new grains are lower than for the porphyroclast or its fragments (0.7-1) (Fig. 8b). Low-angle boundaries are typically observed oriented ~~parallel~~at high angle to the ~~shortening direction~~stretching lineation, indicating that they ~~rather~~ represent healed cracks associated with a slight misorientation ~~and do not indicate~~ rather than indicating subgrains (Fig. 8a). Curved low-angle boundaries bounding subgrains were not observed. The orientation of the new grains scatters around the orientation of the host crystal (Fig. 8c, d). The misorientation angle distribution shows an excess of low and deficit of high misorientation angles for new grains compared to a random distribution (Fig. ~~8e).~~8e particularly for correlated (neighbouring) measurements).

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4.4. Monophase albite matrix alternating with quartz layers

In the fine-grained matrix, layers of almost purely albitic plagioclase Ab_{97-100} (i.e., similar or slightly more Ab-rich compared to plagioclase porphyroclasts) alternate with quartz-rich layers

(Fig. 9; Appendix 1, Table 1). This mylonitic matrix is often deflected by albite porphyroclast and can also be deflected by albite aggregates replacing former porphyroclasts (~~Sect~~sect. 4.3). The microstructure of the layers differs characteristically in their grain size and shape. Based on these two properties, we distinguish two endmembers of quartz-albite matrix microstructure: Type A) The albite grains in the a few hundred µm wide layers are isometric (aspect ratio: 1 – 1.3) with grain diameters varying between 10 – 70 µm, in average of about 15 µm (Fig. 9, 10). The grains usually show no twinning and have a low internal misorientation of generally lower than 5°. The grain boundaries are irregular to smoothly curved (Fig. 11). Inclusions of apatite and domains with high porosity are common (Fig. 11). Grains show compositional zoning (arrows in Fig. 11), which is often only apparent in CL images and is therefore probably linked to changes in trace element contents. This zoning might be truncated by the growth of other grains, ~~which is~~ generally in the direction of their long axes (green arrow in Fig. 11b). A weak shape preferred orientation (SPO) parallel to the foliation can be deflected around the largest porphyroclasts (Fig. 10 a, b). The misorientation angle distribution (Fig. 10c) and ~~pole figures~~polefigures (Fig. 10d) reveal a random texture. Associated quartz-layers are typically a few hundred µm wide and composed of coarse-grained aggregates (diameter of 100 – 1000 µm, Figs. 2c, d, 9a, b). Quartz in layers shows undulatory extinction, subgrains and sutured grain boundaries (Fig. 9a, b).

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Type B) The albite grains in the layers typically a few tens of µm wide are ~~lens-shaped~~ elongate (aspect ratio: in average 2.3 and up to 9) and show a marked SPO. The average grain diameter is with 30 µm larger than in the type A microstructure (Fig. 9 c, d, Fig. 12). Similar to the type A microstructure, there is no apparent crystallographic preferred orientation (CPO) of albite and grains have a low internal misorientation (Fig. 12b, c). Some K-feldspar can be present as larger clasts (Fig. 12b) or as irregular flakes (Fig. 13a). The grain boundaries are mostly serrated but can vary to smoothly curved and even straight, then they are at low angle to the foliation (Fig. 13a, b). Straight segments can be parallel to the traces of (001) and (010) cleavage

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~~planes~~plane, representing energetically favoured boundaries~~.~~ (e.g., Tröger, 1982). The sutures are affected by intragranular cracks, indicated by ~~trail~~trails of pores at ~~low~~high angle to the ~~shortening direction~~stretching lineation (arrows in Fig. 13a, b). Numerous tiny apatite needles occur in zones generally restricted to the centre of the grains but can be cut off by grain boundaries (Fig. 13c) or microcracks. Rarely, grains with twins occur (Fig. 13e). Some grains show Ca-enriched zones and areas with a higher porosity (Fig. 13e, f). The porosities parallel to the short axes of grains, the elongate shape and the zoning indicate that grains grew ~~parallel to the stretching lineation. In general, samples that show the type B matrix record an overall higher strain compared to samples with type A matrix, as indicated by the fine-grained quartz layers with CPO, which are up to several mm long and a few tens of µm wide (Fig.~~ at boundaries perpendicular to the stretching lineation.~~2a, b, 9c, d, 12a, b, d).~~ Generally, new albite grains do not show an orientation contrast observable by BSE imaging, in contrast to twinned remnants of porphyroclasts (Fig. 7).

Samples that show the type B matrix microstructure are interpreted to correlate to a higher strain because of the high aspect ratio (up to 9) and narrow spacing of the alternating quartz-albite layers (tens of µm) compared to the type A microstructure with a larger spacing of the layers of a few hundreds of µm and a lower aspect ratio (Fig. 2a, b, 9c, d, 12a, b, d). These microfabrics correlate with the observation from the field, where samples showing a type B microstructure are characterized by a more narrow spacing of the foliation planes, lower abundance and diameter of porphyroclast as well as a more pronounced stretching lineation.

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5. Discussion

In the following, we discuss the deformation and replacement mechanisms of feldspar leading to the mylonitic fabric and implications on the Alpine deformation.

5.1. Interface-coupled K-feldspar replacement by albite

The replacement of K-feldspar by albite is a widely observed reaction in deforming granitoids at low temperatures. Different types of replacements of K-feldspar by albite have been discussed, which can be divided into two groups:

1) Neocrystallisation or heterogeneous nucleation during metamorphic reactions and/or precipitation from the pore fluid, produces distinct albite grains without any crystallographic relationship to the replaced K-feldspar. The replacements often appear in strings and patches inside the host grain and may be related to fractures (e.g. Fitz Gerald ~~&~~and Stünitz, 1993; Stünitz, 1998; Menegon et al., 2013).
2) Interface-coupled dissolution of K-feldspar (or plagioclase) and spatially coupled precipitation of albite leads to a strong structural coherence across the reaction interface, i.e. of the primary mineral on the ~~orientation of~~orientationof secondary mineral as found in rocks (Plümper ~~&~~and Putnis, 2009; Putnis, 2009) and experiments (Norberg et al., 2011; Hövelmann et al., 2010). These studies reported that the new ~~albite might~~albitemight be porous and might contain secondary inclusions. Norberg et al. (2011) observed associated microcracking in the K-feldspar adjacent to the reaction front. The dissolution of K-feldspar has been found to be orientation-dependent (Norberg et al., 2011). ~~Sawtooth-shaped~~Cuspate protrusions of albite growing into the host K-feldspar have been found to be characteristic of such interface-coupled replacements (Norberg et al., 2011).

The ~~sawtooth-shaped~~cuspate boundaries between new grains of albite and K-feldspar porphyroclasts are interpreted to indicate interface-coupled replacement (Fig. 6~~). The~~), supported by the porosity and apatite inclusions in albite replacing K-feldspar ~~support also this assumption~~ (Fig. 6b, d). The K-feldspar replacement is independent ~~on the~~from the orientation ~~to~~of the ~~shortening or~~ boundary to the foliation and stretching ~~lineations~~lineation and is therefore interpreted to be not directly related to the strain~~. –~~ field during deformation, not excluding some influence of higher strain along the boundary compared to within the crystal. The driving force is interpreted to be the difference in solubility between albite and K-feldspar at the given greenschist-facies metamorphic conditions (Putnis, 2009). Whereas locally albite grew to replace K-feldspar, K must have been transported through the pore fluid, either to form metamorphic phengitic mica in the foliation plane or to precipitate K-feldspar in polyphase strain shadows (see chapter 5.4.).

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The albite in grains along intragranular fractures within K-feldspar (Fig. 2b, 5d) might represent neocrystallization of albite replacing K-feldspar. As the intragranular fractures perpendicular to the stretching ~~direction (X)~~lination (x), these sealed fractures might represent ~~sites of dilation, it is more likely that the~~ prismatic strain shadows, i.e. albite may have precipitated from the pore fluid ~~without~~and not necessarily replacing K-feldspar~~, i.e. these sealed fractures rather represent strain shadows~~.

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5.2. Strain-~~driven~~induced replacement of albite

~~Albite porphyroclasts are mostly deformed at sites of shortening, commonly associated with dislocation glide indicated by bent mechanical twins (Fig. 7a-e). The areas of high strain~~Albite porphyroclasts are mostly deformed at boundaries parallel to the foliation, commonly associated with bent mechanical twins (Fig. 7a-e). Bent twins are corresponding to an undulous extinction indicating a continuous internal misorientation, which is usually taken to result from the presence of geometrically necessary dislocations (e.g., Nicolas and Poirier, 1976; Poirier, 1985; Wheeler et al., 2009), though some microcracking might also be involved, as pointed out by Tullis and Yund (1987). For albite this continuous internal misorientation is not associated to distributed healed microfractures, as observed for K-feldspar (compare Figs. 5 and 7), which is taken to indicate a relative higher importance of dislocation glide for the deformation of albite compared to K-feldspar. Strained areas (fractures, porphyroclast boundaries) parallel to the foliation are replaced by new, strain free grains that are generally not twinned (Fig. 7b, d, e-f).

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The composition of the new albite grains can be the same as that of the replaced porphyroclast, though it can also show slightly higher Na-content, as already reported by Stöckhert (1987). Plagioclase with Ca-richer compositions occurs locally as thin rims at grain boundaries of new grains with no systematic occurrence (Figs. 7f). Because new strain-free albite grains replace twinned porphyroclasts with internal misorientation at ~~sites of shortening~~boundaries parallel to the foliation (Figs. -7e, f, 8a, b~~),~~) and along intragranular microcracks~~ and kink bands~~ parallel to the foliation (Fig. 7a, b), the replacement is interpreted to be driven by the reduction in stored strain energy. Strain-induced grain boundary migration ~~coupled with~~and formation of growth rims following dislocation glide and microfracturing is consistent with an orientation scatter around the orientation of the host porphyroclast (Fig. 8d, f). The similar composition of the new albite compared to the replaced porphyroclasts, with a tendency of a slightly increased Na-content, suggests a contribution of chemical driving forces although strain-induced grain boundary migration is dominating (Stöckhert, 1982; Stünitz, 1998). Whereas dislocation glide is indicated by bent~~, kinked~~ and twinned porphyroclasts and fragments with internal ~~misorientations~~misorientation, we did not observe subgrains in deformed fragments (Fig. 8a-c), even not in strongly bent ~~and kinked~~ porphyroclasts (Fig. 7 a, b, e~~) and no sutured grain boundaries indicating dynamic "bulging recrystallization" (e.g., Drury et al., 1985; Stünitz, 1998~~). This is consistent with the general finding that albite shows only little evidence of dislocation climb with dynamic recovery and recrystallization at T ≤ 550°C (e.g., Tullis, 1983; Fitz Gerald ~~& Stünitz, 1993; Kruse & Stünitz, 2001).~~ and Stünitz, 1993; Kruse and Stünitz, 2001).~~Dislocation climb necessary for dynamic recovery and recrystallization requires intracrystalline diffusion. At the investigated temperatures (<550°C), the NaSi ↔ CaAl interdiffusion rates for plagioclase are very low (Yund, 1986; Korolyuk & Lepezin, 2009). In the presence of water, the diffusion coefficient is several magnitudes higher, which might account for the weakening observed in experiments where fluid is present (e.g. Rybacki & Dresen, 2004). Only few studies report subgrains in albite deformed at greenschist facies~~

Commented [F37]: Point 32, review #1; Points 34-36, review #2

~~conditions, sometimes together with shear bands (Fitz Gerald & Stünitz, 1993; Eberlei et al., 2014). TEM studies also show that sufficient dislocation climb to produce subgrains is effective only at temperatures from the middle amphibolite upward (e.g. White, 1975; Stünitz et al., 2003). The experiments by Tullis & Yund (1985) show that grain boundaries may migrate into areas of higher dislocation density introduced by microfracturing driven by the reduction in strain energy (Tullis & Yund, 1987) at conditions, at which recovery is not active.~~

We suggest that albite porphyroclasts deform in the regime of low-temperature plasticity, where dislocation climb is ineffective and where dislocation glide leads to strain hardening and microfracturing. Additionally, dislocations can be induced by microfracturing (Tullis and Yund, 1987). Subsequently, grains grow by strain-induced grain boundary migration, where crystalline volume with higher strain energy is dissolved and strain-free crystalline volumes precipitated, as ~~opposed to solid-state grain boundary migration with effective dislocation climb.~~suggested by Tullis and Yund (1987). Growth can additionally be by precipitation along areas of lower solubility leading to growth rims with a shape-preferred orientation with long axes in the foliation plane. Strain-induced grain boundary migration might be enhanced by chemical disequilibrium (Stöckhert, 1982; Stünitz, 1998). ~~This~~Our interpretation of strain-induced replacement is similar to the “micro-crush zones” described by Tullis ~~&~~and Yund (1992) associated with undulous extinction, shear bands and grain size reduction that are usually associated to crystal plastic mechanisms (Mclaren ~~&~~and Pryer, 2001; Stünitz et al., 2003). This process is also similar to the “neocrystallization” in the sense of Fitz Gerald ~~&~~and Stünitz (1993) and Menegon et al. (2013), which may or may not cause some compositional variations, dependent on the local fluid present. We, however, ~~prefer~~suggest the term “strain-~~driven~~induced replacement” for the nucleation by low-temperature plasticity (associated dislocation glide and microfracturing) and growth ~~by strain-induced grain boundary migration~~to stress firstly the importance of dislocation glide (as opposed to the term “micro-crush zones” that stresses brittle mechanisms) and secondly to stress the difference to

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Commented [F39]: Point 37, review #2 precipitation with nucleation of new phases from the pore fluid ~~at sites of dilation~~ in strain shadows~~.~~ (as opposed to the term “neocrystallization”).

5.3. Intragranular fracturing of K-feldspar

~~In contrast,~~ K-feldspar porphyroclasts deformed dominantly by intragranular fracturing with no comparable strain-~~driven~~induced replacement associated with a grain size reduction as observed for albite. ~~Intragranular fractures at low angle to the shortening direction are the dominating deformation microstructures, which did not result in major grain size reduction.~~ A preferred crystallographic relation of the intragranular fractures was not detected~~,~~ given their orientation at high angle to the stretching lineation independent on crystallographic orientation (Fig. 5), ruling out a major influence of cleavage fractures~~, although feldspars do show perfect cleavage after (001) and one good cleavage after (010) (e.g., Tröger, 1982).~~. Single fractures are sealed with albite, K-feldspar and quartz representing prismatic strain shadows, or they are healed (Fig. 5). Bending of K-feldspar porphyroclast associated to undulous extinction is restricted to sites of distributed microcracking~~, where some influence of dislocation glide is probable (Fig. 5a).~~ (Fig. 5a).The high amount of healed microcracks at high angle to the stretching lineation indicates that here, microfracturing was dominating over dislocation glide in the bending of the crystal, as opposed to albite porphyroclasts (compare Fig. 5a and Fig. 7 a, e). In contrast to plagioclase, where mechanical twinning is commonly observed, mechanical twinning of K-feldspar is hindered by the Si/Al-ordering ~~and has not been observed~~ (Tullis, 1983).

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Reaction weakening of K-feldspar, commonly in association with myrmekites~~,~~ is known to play a major role during grain size reduction and ductile deformation at many metamorphic conditions (e.g., Simpson and Wintsch, 1989; Tsurumi et al., 2003; Ree et al., 2005; Menegon et al., 2006, 2008, 2013; Abart et al., 2014). In the mylonitic pegmatites described here, myrmekitic replacements are very rare and apart from the ~~sawtooth-shaped~~cuspate replacements, K-feldspar porphyroclasts are well preserved. Thus, reaction weakening of K-feldspar is rheologically not relevant for the mylonitic deformation described here.

5.4. Precipitation ~~at sites of dilation~~in strain shadows

The occurrence of polyphase aggregates of K-feldspar, albite, mica and quartz ~~located at dilatational sites~~in strain shadows between fragments of tourmaline and feldspar porphyroclasts, as well as surrounding porphyroclast (Figs. 2a, b, 4a-c, 5c, d), with random texture and absent systematic crystallographic relationships indicate that these aggregates represent precipitates of a saturated pore fluid during deformation by dissolution-precipitation creep (~~Passchier & Trouw, 2005).~~ e.g., Groshong, 1988; Passchier and Trouw, 2005; Wassmann and Stöckhert, 2013). That few grain orientations in the strain shadow correlate with that of the host crystal is interpreted to be due to the presence of fragments of the host crystal (Fig. 4d). The precipitation of K-feldspar, quartz and albite in strain shadows and albite growth rims is restricted to ~~sites of dilation, i.e.~~boundaries at high angle to the stretching lineation (x), i.e. controlled by strain, yet an additional chemical driving force is clearly not ruled out but rather probable. Additionaly, some replacement might also occur in strain shadows. The sites of dissolution are much more difficult to identify, as the material has been removed.

A polyphase matrix of K-feldspar, albite quartz and mica in mylonitic granitoids is often attributed to fine-grained reaction products (e.g~~.,~~., Stünitz ~~&~~and Fitz Gerald, 1993; Rosenberg ~~&~~and Stünitz, 2003; Kilian et al., 2011). Other authors, suggest polyphase matrix to develop by mechanical phase mixing in mylonites at highest strain (Fliervoet, 1995). In the mylonitic pegmatites reported here, however, no indication of active “phase mixing” is observed and we attribute the occurrence of a polyphase matrix to precipitation. Also, the ~~highest strain in the~~characteristic mylonitic microstructure of the pegmatites is associated not with a polyphase matrix but with the monophase quartz and ~~feldspar~~albite layers.

Commented [F42]: Points 2, 10 28, 30, 40, 46, review #2

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5.5. Formation of monophase albite layers

Based on our observations that~~ the~~ albite in layers shows the same characteristics as albite grains replacing albite porphyroclasts (missing subgrains and internal misorientations, apatite inclusions, weak chemical zoning and porosity, and remnants of twinned porphyroclast fragments), we suggest, that the strain-~~driven~~induced replacement of albite is the most important process of grain size reduction to form the monophase albite layers (Fig. 14). Additionally, ~~some~~part of the albite in the mylonitic matrix stems from the replacement of K-feldspar (~~Sects~~sects. 4.2 and 5.1), as suggested by K-feldspar-relicts (Figs. 12b; 13a). Because the matrix layers comprise about 95% albite, independent on the ratio of K-feldspar to albite porphyroclasts, we suggest that albite is taking up a higher amount of strain as compared to K-feldspar. Dislocation creep of albite is ruled out as main process to form the fine-grained almost monophase albite layers, given a missing systematic CPO as well as missing evidence of effective dislocation climb. Also, precipitation from the pore fluid as dominating process can be ruled out, given the monophase composition of the layers, in contrast to polyphase aggregates in ~~dilation sites.~~strain shadows. Cataclasis would suggest a higher amount of twinned and deformed fragments. Instead, only very rarely twinned grains are observed (Fig. 13e).

~~After~~We suggest that after grain size reduction~~ by~~, the ~~strain-driven replacement of ~~fine-grained albite~~,~~, matrix was undergoing a mixture of dissolution-precipitation processes, microcracking and sliding of grains, commonly referred to as granular flow (e.g., Behrmann and Mainprice, 1987; Stünitz and Fitz Gerald, 1993; Jiang et al., 2000~~), i.e. sliding of grains relative to each other probably has played a major role in the fine-grained albite matrix. Straight~~). Sliding might have occurred along straight boundaries weakly inclined to the foliation (Fig. ~~13b) might represent boundaries along which sliding occurred. This and the weak zoning in association with microcracks~~13b). Microcracking is indicated by the fractures at ~~low~~high angles to the ~~shortening direction~~foliation (Fig. 13a, b, e~~) indicate that granular flow was assisted by~~

~~microcracking and~~). The weak zoning of grains (Figs. 11 and 13) suggests the involvement of dissolution-precipitation~~ processes~~. Granular flow would also cause weakening of a domainal CPO resulting from the replacement of albite porphyroclasts (e.g. Jiang ~~and Wheeler,~~et al., 2000; Hildyard et al., 2011).

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Quartz layers of coarse recrystallized grains systematically correlate with albite layers of small isometric grains in the type A matrix microstructure (sect. 4.4; Figs. 9a, b; 10; 11). In contrast, narrow quartz layers with fine-grained quartz aggregates and marked CPO are correlated with elongate coarser albite in the type B matrix microstructure (Sect. 4.4; Figs. 9c, d; 12; 13). The elongate shape of albite and zones of high porosity at boundaries at high angle to the stretching lineation in the type B matrix microstructure indicates ~~oriented~~ growth ~~parallel to the stretching lineation, i.e. overgrowth at sites of dilation, as indicated~~ by ~~the growth zones associated with porosity parallel to the shortening direction~~precipitation, resulting in a shape-preferred orientation (Fig. 13e, f). The microstructure correlates with the overall strain of the mylonitic matrix (Fig. 14). ~~The~~ In samples with higher ~~the~~ overall strain, ~~the coarser and more elongate the~~ albite grains in the layers are coarser and more elongate and ~~the finer grained~~ quartz aggregates ~~with~~ are finer-grained and have a marked CPO~~. Therefore, we suggest that the albite grains grew parallel to the stretching lineation, forming a higher aspect ratio by preferred growth~~.

~~5.6. Rheologically dominant processes~~

5.6. Implications for rock rheology and deformation history

The prismatic strain shadows of polyphase material between fragmented tourmaline and feldspar as well as strain shadows surrounding ~~porphyroclast~~porphyroclasts indicate that dissolution-precipitation creep did play a role in the rheology of the rocks. Yet, other indicators of dissolution-precipitation creep, as for example evidence of dissolved feldspar porphyroclasts

~~at sites of shortening, i.e. strain caps, are remarkably low. In contrast, the monophase quartz and albite layers are the main characteristic of the mylonitic microstructure and clearly correlated with strain. Therefore, strain-induced replacement of albite with granular flow and dislocation creep of quartz are interpreted to rheologically dominate over dissolution-precipitation creep.~~along boundaries parallel to the foliation, i.e. strain caps, are remarkably low. The monophase alternating quartz and albite layers are the main characteristic of the mylonites. The dominating process of grain size reduction of feldspar is interpreted to be the strain-induced replacement of albite with associated dislocation glide and fracturing (Fig. 14). Subsequent growth by strain-induced grain boundary migration and formation of growth rims by precipitation resulted in a SPO (Fig. 14), which took place probably simultaneously together with granular flow and dislocation creep of quartz. As such, for considering the rock's rheology, these different deformation mechanisms and associated processes have to be taken into account, where the relative contributions additionally vary with time. In contrast, dissolution-precipitation creep with dissolution along boundaries parallel to the foliation and precipitation with nucleation of new phases in strain shadows is interpreted to play an only subordinate role for the formation of the mylonitic alternating quartz-albite layers, although precipitation of albite forming elongate grains with SPO in monophase aggregates is important. Furthermore, a major role of dislocation creep of feldspar (i.e., deformation by dislocation glide with simultaneous dynamic recovery) on the formation of the mylonitic microstructure as may be suggested by monophase layers of fine-grained feldspar aggregates, is not supported by any further microstructural observation (e.g., systematic missing of LAGBs) and therefore interpreted to be rheologically not relevant during deformation.

The observation of newly precipitated grains from the pore fluid between tourmaline and K-feldspar fractures at ~~sites of dilation~~strain shadows as well as the microcracks in K-feldspar that are cut off by the wedge shaped albites replacing K-feldspar (Figs. 2a, b; 3c, d) indicate growth of grains after fracturing and during ongoing deformation. The observation of the deflected mylonitic foliation around former porphyroclasts, which are now replaced by new grains (Fig. 2c, d; 7c), indicates that the new grains grew after~~,~~ or~~ more probably,~~ during the formation of the mylonitic layers, but not before. Thus, strain-induced replacement of albite must have played an important role during an early stage of deformation and was ongoing during granular flow. Thus, a specific sequence of different deformation episodes at markedly different metamorphic stages, as had been discussed, is not apparent (Stöckhert, 1987; Mancktelow et al., 2001). The indication of the type A matrix microstructure being dominating in the eastern area and the type B matrix microstructure representing in comparison higher strain in the western area (Fig. 1) might be correlated with higher metamorphic temperature conditions in the western area, as the amount of uplift and erosion since the intrusion of magmatic bodies at 30 Ma is increasing from about 10 km in an eastern area of the Rieserferner to about 15 to 25 km in the Rensen area in the west (Trepmann et al., 2004).

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6. Conclusions

The mylonitic pegmatites record the deformation behaviour of feldspar at greenschist facies conditions. Based on our observations and discussions we draw the following conclusions:

1. K-feldspar porphyroclasts deformed dominantly by fracturing and only subordinate dislocation glide, without major grain size reduction. Healed or sealed intragranular fractures in large porphyroclasts at ~~low~~high angle to the ~~shortening direction~~stretching lineation are the dominating deformation microstructures of K-feldspar (Fig. 5).
2. Interface-coupled replacement of K-feldspar by albite is mainly driven by chemical disequilibrium ~~and not by strain,~~ as indicated by the ~~sawtooth-shaped~~cuspate albite-K-feldspar phase boundaries independent on the orientation of the boundary to the foliation or the stretching lineation (Fig. 6).
3. Grain size reduction of albite porphyroclasts is by combined fracturing~~,~~ and dislocation glide, i.e. low-temperature plasticity. Dislocation glide is indicated by bent and twinned

remnant host albites with internal misorientation. Evidence of significant amount of dislocation climb allowing effective dislocation creep with dynamic recovery of feldspar is systematically missing (no subgrains, negligible internal misorientation of new grains; Figs. 10c, d, 12c, e).

~~3.~~4. Subsequent strain-induced grain boundary migration and formation of growth rims produced aggregates of strain-free albite grains with SPO at ~~sites of shortening~~porphyroclast boundaries parallel to the foliation (Figs. 7c-f, 8). The observed tendency of slightly enriched Na-content (decrease of Ca-content) of the new albite grains compared to albite porphyroclasts is in agreement with an additional, though subordinate driving force for grain boundary migration by chemical disequilibrium (Stöckhert, 1982).

~~4.~~1.~~Dislocation glide is indicated by bent, kinked and twinned albite with internal misorientation. Evidence of significant amount of dislocation climb allowing effective dislocation creep with recovery of feldspar is systematically missing (no subgrains, negligible internal misorientation of new grains, random texture Figs. 10c, d, 12c, e).~~

~~5. Granular flow of the new albite grains assisted by fracturing and dissolution-precipitation with overgrowth of albite parallel to the stretching direction in samples of high strain led to the monophase albite ribbons (Figs. 9-13).~~

~~6.~~5. Monophase quartz ~~ribbons~~layers formed dominantly by dislocation creep (dislocation glide, dynamic recovery and ~~grain boundary migration~~recrystallization) of quartz, as indicated by sutured grain boundaries, CPO, subgrains and undulatory extinction (Figs. 2c, 9, 12a, d). Some influence of dissolution-precipitation creep cannot be excluded; though microstructural evidence has not been observed.

~~Although evidence of dissolution-precipitation creep is evident by polyphase strain shadows and sealed fractures of porphyroclasts, the main strain of the mylonitic pegmatites is correlating with the alternating albite and quartz layers. Strain-induced replacement of albite and granular~~

~~flow assisted by fracturing and dissolution-precipitation as well as dislocation creep of quartz are the rheologically dominant processes recorded by the pegmatitic mylonites.~~

6. Granular flow of the new albite grains with overgrowth of albite forming a SPO together with quartz dislocation creep is interpreted to result in the alternating monophase albite-quartz layers (Figs. 9-13).

For considering the rock's rheology, these different deformation mechanisms and associated processes have to be taken into account, where the relative contributions additionally vary with time.

Acknowledgements

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