Grain-size reduction of feldspars by fracturing and neocrystallization in a low-grade granitic mylonite and its rheological effect

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Abstract

Feldspar grain-size reduction occurred due to the fracturing of plagioclase and K-feldspar, myrmekite formation and neocrystallization of albitic plagioclase along shear fractures of K-feldspar porphyroclasts in the leucocratic granitic rocks from the Yecheon shear zone of South Korea that was deformed under a middle greenschist-facies condition. The neocrystallization of albitic plagioclase was induced by strain energy adjacent to the shear fractures and by chemical free energy due to the compositional disequilibrium between infiltrating Na-rich fluid and host K-feldspar. With increasing deformation from protomylonite to mylonite, alternating layers of feldspar, quartz and muscovite developed. The fine-grained feldspar-rich layers were deformed dominantly by granular flow, while quartz ribbons were deformed by dislocation creep. With layer development and a more distributed strain in the mylonite, lower stresses in the quartz-rich layers resulted in a larger size of dynamically recrystallized quartz grains than that of the protomylonite.

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1. Introduction

Grain-size reduction can trigger a change in rheology of deforming rocks due to a switch in the dominant deformation mechanism (e.g., White et al., 1980). This rheological change, in turn, may induce strain localization in the lithosphere (e.g., Rutter and Brodie, 1988; Braun et al., 1999), or soften the subducting slab as a whole causing a change in the mantle convection mode (e.g., Karato et al., 1998; Čižková et al., 2002). Grain-size reduction also facilitates reactions by increasing the surface area (e.g., Evans, 1988) or may lead to change in magnetic properties (e.g.,

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Halgedahl and Ye, 2000). Grain-size reduction under non-coaxial deformation can also induce a strong lattice preferred orientation, resulting in a significant change in seismic wave propagation (Jung and Karato, 2001).

Grain-size reduction can be achieved by cataclasis, reaction, dynamic recrystallization and phase transformation. In feldspar, the most abundant crustal mineral, grain-size reduction may be produced by cataclasis and neocrystallization of albitic plagioclase from feldspar porphyroclasts under greenschist facies conditions (Fitz Gerald and Stüntz, 1993). Deformation-induced myrmekite formation also incurs feldspar grain-size reduction, but this has been known to be effective in epidote–amphibolite facies and higher grade conditions (Vernon et al., 1983; Simpson, 1985; Simpson and Wintsch, 1989; Pryer, 1993). However, Tsurumi et al. (2003) recently reported that myrmekite formation, together with fracturing, can considerably reduce the feldspar grain size under middle greenschist facies conditions. In this paper, we report that all these processes of fracturing, neocrystallization of albitic plagioclase along fractures and myrmekite formation contribute to significant grain-size reduction of feldspar in granitic mylonites from a middle greenschist-facies shear zone. We also show that feldspar grain-size reduction not only leads to a switch in the dominant deformation mechanism in feldspar-rich layers, but also to a change in the size of dynamically recrystallized grains in quartz-rich layers of the mylonites.

2. Microfabrics

Samples of the granitic mylonites were collected from an outcrop within the Yecheon shear zone which is a branch of the right-lateral Honam shear zone system of the Jurassic in South Korea (Yanai et al., 1985; Park et al., in press). There is a transition from a weakly deformed to highly deformed granitic rocks in the outcrop, referred to as protomylonite and mylonite, respectively, in this paper.

The protomylonite consists of porphyroclasts (0.5 to 14 mm in length) of K-feldspar (38%), plagioclase (5%), and matrix of quartz (25%), plagioclase (18%), K-feldspar (9%) and muscovite (4%) with a minor content of biotite, garnet, chlorite, zircon and opaque minerals (Fig. 1a). The modal percentage of the constituent minerals was obtained by point counting on thin-sections stained with Na-cobaltinitrite (for K-feldspar) and K-rhodizonate (for plagioclase). On the other hand, the mylonite is composed of porphyroclasts (0.5 to 6 mm in length) of plagioclase (17%) and K-feldspar (11%), and matrix of quartz (33%), muscovite (18%), plagioclase (11%), K-feldspar (8%) and calcite (1%) with a minor content of chlorite, zircon and opaque minerals (Fig. 1b). There is a significant increase in the muscovite, plagioclase and quartz contents, and a remarkable decrease in K-feldspar content compared with the protomylonite. Also, the feldspar porphyroclasts of the mylonite decrease both in size and amount. It can be seen in the mylonite that matrices of feldspar, quartz and muscovite form interconnected layers.

2.1. Protomylonite

2.1.1. K-feldspar

K-feldspar grains are deformed dominantly by fracturing, although many grains show patchy undu-
latory extinction. Most of the intragranular/transgranular shear fractures are subparallel to the bulk shear plane, while extension fractures tend to be at a high angle to the bulk shear plane (Fig. 2). Occasionally, antithetic shear fractures utilizing cleavage planes within K-feldspar porphyroclasts occur at a high angle to the bulk shear plane (Fig. 2a). The extension fractures usually follow the cleavage planes of K-feldspar, and are filled by quartz, muscovite or chlorite. The precipitation of quartz with some muscovite and K-feldspar also occurs in the pressure shadow areas of K-feldspar porphyroclasts.

Along many of the shear fractures of K-feldspar porphyroclasts, fine-grained plagioclase grains (5 to 40 μm) occur as a band with a width of two- to five-grains (Fig. 2b, c and d). These plagioclases are albite (An5–15), as shown in a later section of this paper. The phase boundaries between the host K-feldspar and the neocrystallized albite plagioclases are wavy or lobate, suggesting phase boundary migration, and thus a reaction. In the backscattered SEM micrograph of Fig. 2d, the neocrystallized plagioclase grains appear to have some zoning patterns. However, no compositional variation was observed in X-ray intensity maps of Na, K, Ca and Al.

On K-feldspar porphyroclast faces subparallel to the mylonitic foliation, myrmekitic intergrowth of plagioclase and quartz occurs (Fig. 3). These myrmekitic plagioclases are albite (An1–12), as shown later. The myrmekite lobes commonly embay the margins of K-feldspar porphyroclasts. The myrmekite formation together with neocrystallization of albite plagioclase and fracturing significantly reduces the K-feldspar grain size.

2.1.2. Plagioclase
For the deformation of plagioclase porphyroclasts, fracturing is dominant as in K-feldspar, although some grains show mechanical twinning and kinking. Most grains show patchy undulatory extinction. Cleavage fractures within plagioclase porphyroclasts are filled mostly by K-feldspar and occasionally by muscovite or quartz (Fig. 4a). In the pressure shadow areas and boudin necks of plagioclase porphyroclasts, K-feld-
spar precipitates with some quartz and muscovite, and some fractured fragments of plagioclase are present (Fig. 4).

Incipient development of alternating layers of fine-grained feldspar, quartz and muscovite occurs in the protomylonite (Fig. 4d). The feldspar-rich layer is composed mainly of subrounded to subangular albite plagioclase (10 to 100 \( \mu \text{m} \) in length) with interstitial K-feldspar and subordinate quartz filling the spaces between the plagioclase fragments.

2.1.3. Quartz

The quartz grains in the protomylonite commonly show patchy or sweeping undulatory extinction and deformation bands. When quartz grains occur between feldspar porphyroclasts, they are highly stretched parallel to the mylonitic foliation. Most of quartz grains show core-and-mantle structures with diffuse grain boundaries (Fig. 5a). Recrystallized grains occur at the boundaries of old grains with their size (2–6 \( \mu \text{m} \)) similar to that of the subgrains at the old grain mantles, indicating subgrain rotation recrystallization although the recrystallization appears to be somewhat incomplete (Hirth and Tullis, 1992; Stipp et al., 2002).

We measured orientation of quartz c-axes of the protomylonite using an automated fabric analyzer apparatus developed at the University of Melbourne (Russell-Head and Wilson, 2001; Wilson et al., 2003). The quartz c-axis fabric shows a single girdle pattern at a high angle to the mylonitic foliation with a maximum in the Y-axis (i.e., 90° from the mylonitic lineation on the foliation plane; Fig. 5b). All these microfabrics of the protomylonite indicate that the quartz grains were deformed by dislocation creep.

2.2. Mylonite

The most remarkable differences between the mylonite and the protomylonite are compositional layering, feldspar grain-size reduction (induced by fracturing, neocrystallization of albite plagioclase and myrmekite formation), increase in the muscovite, quartz and plagioclase contents, and decrease in the K-feldspar content in the mylonite. Also, post-mylonitization calcite micro-veins occasionally occur in the mylonite. The feldspar-, quartz- and muscovite-rich layers that define the mylonitic foliation are 30–300, 20–500 and 10–50 \( \mu \text{m} \) thick, respectively (Fig. 6a).

The feldspar-rich layer consists mostly of albite plagioclase and interstitial K-feldspar, with some muscovite, quartz and opaques (Fig. 6b and c). The interstitial K-feldspars appear to fill the spaces between monocristalline or polycristalline plagioclase fragments. The spaces filled by K-feldspar tend to be at a high angle to the mylonitic foliation. The albite plagioclase grains in the layer, many of them showing patchy undulatory extinction, are subangular to sub-rounded in shape and mostly 10–30 \( \mu \text{m} \) in length although remnants of plagioclase porphyroclasts (up to 100 \( \mu \text{m} \) long) occasionally occur in the layer (Fig. 6d). The remnants of plagioclase porphyroclasts show some zoning patterns in the backscattered SEM micrograph. However, no chemical zoning was identified in compositional profiles from electron microprobe analysis data. The pressure shadow areas and extension fractures of the plagioclase porphyroclast remnants are filled by precipitated K-feldspar.

To check if there is any lattice preferred orientation of albite plagioclase in the feldspar-rich layers
of the protomylonite and mylonite, electron back-scattered diffraction (EBSD; Dingley and Randle, 1992) analysis was performed at the University of California at Riverside using a scanning electron microscope FEG XL-30 equipped with an HKL’s EBSD system. The spatial resolution of this system is about 1 \( \mu \text{m} \). We used an accelerating voltage of 20 kV and working distance of 15 mm. To remove surface damages, specimens were polished using the SYTON (a colloidal silica) fluid for chemical–mechanical polishing (Lloyd, 1987). The specimen surface was inclined at 70° to the incident beam. All EBSD patterns of plagioclase were manually indexed using the HKL’s Channel software. In the pole figures of Fig. 7, it can be seen that the albitic plagioclase grains in the feldspar-rich layer do not show any strong lattice preferred orientation.

Fig. 4. Microstructures of plagioclase porphyroclasts in protomylonite. (a) Backscattered SEM micrograph of K-feldspar precipitation in pressure shadow and cleavage fractures of a plagioclase porphyroclast. Abbreviations are the same as in Fig. 3. (b) Enlarged backscattered SEM micrograph of K-feldspar precipitation in a plagioclase porphyroclast. (c) Backscattered SEM micrograph of the feldspar-rich layer showing fine-grained albitic plagioclase with interstitial K-feldspar.

Fig. 5. (a) Photomicrograph of quartz grains showing subgrain rotation recrystallization in protomylonite. (b) Pole figure of quartz c-axes in protomylonite. Quartz c-axes were measured in the surrounding areas as well as in the area of (a). Lower-hemisphere, equal-area projection.
Fig. 6. Microstructures of mylonite. (a) Photomicrograph of the alternation of feldspar (F)-, quartz (Q)- and muscovite (M)-rich layers. Cross-polarized light with both upper and lower polars rotated 45° counterclockwise. (b) Enlargement of feldspar-rich layer. (c) Backscattered SEM micrograph of (b). (d) Enlargement of (c). Abbreviations are the same as in Fig. 3.

Fig. 7. Pole figures of albitic plagioclase in feldspar-rich layers from (a) mylonite and (b) protomylonite. The north pole corresponds to the normal to the foliation. The east–west direction corresponds to the lineation. Lower-hemisphere, equal-area projection.
On the other hand, the quartz grains of the quartz layers commonly show sweeping undulatory extinction in the mylonite. The quartz grains of the mylonite exhibit core-and-mantle structures with the size of recrystallized grains similar to that of the subgrains at the mantle of old grains, indicating subgrain rotation recrystallization (Fig. 8a) as in the protomylonite. The size of the recrystallized quartz grains (5–25 μm) in the mylonite is, however, much larger than that (2–6 μm) in the protomylonite. Some boundaries of quartz are wavy or lobate, indicating local grain boundary migration. The c-axis fabric of quartz grains shows a single girdle pattern at a high angle to the mylonitic foliation as in the protomylonite (Fig. 8b).

3. Bulk and feldspar chemistries

Bulk rock compositions were measured from the crushed fractions of rock samples using a Philips PW2405 X-ray fluorescence spectrometer at the Korea Basic Science Institute. The major element data for the samples are shown in Table 1. The chemical compositions of the plagioclase and K-feldspar in the two samples were determined by electron microprobe analysis (EPMA) using a JEOL JX-8600 at Korea University.

When comparing the chemical data of the protomylonite with those of the mylonite, not much difference is observed in the SiO₂, Al₂O₃, Fe₂O₃, MgO, MnO and Na₂O contents. However, the CaO content in the mylonite is two times higher than that in the protomylonite, whereas that of K₂O in the mylonite is half of that in the protomylonite (Table 1). The difference in the CaO content reflects the higher plagioclase modal content and occasional post-mylonitization calcite veins in the mylonite. The occurrence of K-feldspar veins in adjacent outcrops within the shear zone may account for the K₂O escaped from the studied outcrop system.

The mineral composition of porphyroclastic K-feldspars both in the protomylonite and mylonite ranges from Or₉₂ to Or₉₈ that is similar to that of precipitated K-feldspars (Fig. 9). The chemical composition of plagioclases varies from An₁ to An₁₅. Myrmekite plagioclase tends to be more albitic than porphyroclastic plagioclase in the protomylonite. The majority of the plagioclase compositions within feldspar-rich layers fall within An₄ to An₁₀ in the mylonite. The plagioclase compositions in the mylonite show no systematic difference in myrmekites, frag-

![Fig. 8. (a) Photomicrograph of quartz grains showing core-and-mantle structure. Cross-polarized light. (b) Pole figure of quartz c-axes in protomylonite. Lower-hemisphere, equal-area projection.](image)

| Table 1 Major element chemistry of protomylonite (ABY009-129) and mylonite (PE001-5) |
|-----------------------------------------------|------------------|------------------|
| Sample No. | ABY009-129 | PE001-5 |
| SiO₂ | 71.65 | 74.63 |
| TiO₂ | 0.02 | 0.05 |
| Al₂O₃ | 15.61 | 14.44 |
| Fe₂O₃* | 0.51 | 0.56 |
| MgO | 0.06 | 0.14 |
| MnO | 0.02 | 0.04 |
| CaO | 0.55 | 1.24 |
| K₂O | 7.00 | 3.67 |
| Na₂O | 3.18 | 3.22 |
| P₂O₅ | 0.06 | 0.08 |
| L.O.I** | 0.42 | 1.25 |
| Total | 99.07 | 99.32 |

N.B. *: total iron, **: loss of ignition.
ments, porphyroclasts and feldspar-rich layers. The composition of the interstitial K-feldspars in the feldspar-rich layer ranges from Or$_{93}$ to Or$_{98}$ in the mylonite (Fig. 9).

The deformation temperatures of the protomylonite and mylonite are estimated to be $355 \pm 44$ and $335 \pm 48 \, ^\circ$C, respectively, with an assumption of 3 kbars pressure, employing the two-feldspar geothermometry on neocrystallized plagioclase and adjoining K-feldspar (Stormer and Whitney, 1985; Green and Usdansky, 1986), although the temperature estimation using the two-feldspar geothermometry at these low temperatures may be inaccurate. The pressure of 3 kbars is assumed because the deformation age of the Yecheon shear zone is close to a late stage of the emplacement of granite plutons in the margins of the shear zone (Kwon and Ree, 1997; Otoh et al., 1999) and also because the emplacement depth is about 10 to 15 km based on hornblende Al geobarometry (Cho and Kwon, 1994). Also, the microfabrics of quartz indicate a greenschist facies condition (see Stipp et al., 2002) together with feldspar compositions.

### 4. Discussion

The myrmekite lobes at K-feldspar porphyroclast faces parallel to the mylonitic foliation described above are similar to those reported by Simpson and Wintsch (1989) and Tsurumi et al. (2003), indicating an interrelationship between deformation and the myrmekite-forming reaction. Deformation-induced K-
feldspar replacement by myrmekite plagioclase and quartz in the Yecheon granitic mylonites can be expressed as follows:

\[
1.05KAlSi_3O_8 + 0.95Na^+ + 0.05Ca^{2+} \\
\text{K-feldspar porphy} = \text{Na}_{0.95}Al_{0.05}Si_{1.1}O_8 + 0.2SiO_2 + 1.05K^+. \\
\text{myrmekite plagioclase} \\
\text{quartz}
\]

\[(1)\]

Simpson and Wintsch (1989) suggested that the aqueous K+ precipitates as K-feldspar in pressure shadows and fractures, as observed in the mylonites studied (see Fig. 5). The aqueous Ca\textsuperscript{2+} and Na\textsuperscript{+} in reaction (1) were presumably derived from the circulating fluids. The K\textsuperscript{+}, Na\textsuperscript{+} and Ca\textsuperscript{2+} in the circulating fluids play key roles, not only in the precipitation of K-feldspar in extensional sites, but also in the myrmekite formation and neocrystallization of fine-grained albitic plagioclase along the shear fractures of K-feldspar porphyroclasts.

The neocrystallization of the fine-grained albitic plagioclase only along the shear fractures of the K-feldspar porphyroclasts suggests that the nucleation was induced not only by strain energy adjacent to the shear fractures, but also by chemical free energy due to compositional disequilibrium between the infiltrated sodium-rich fluid and host K-feldspar (Stünitz, 1998). The strain energy was presumably produced by a high dislocation density localized along the shear fractures as shown by Tullis and Yund (1987), and Fitzgerald and Stünitz (1993). The absence of plagioclase neocrystallization along the fractures of plagioclase porphyroclasts implies that the chemical free energy was too low for nucleation due to only a little compositional disequilibrium between the infiltrated sodium-rich fluid and albitic plagioclase host.

Fig. 10 schematically illustrates the deformation processes of feldspar grains in the mylonitic samples deformed under middle greenschist-facies conditions. Feldspar grain-size reduction was induced by fracturing, myrmekite formation and neocrystallization of albitic plagioclase. With grain-size reduction, fine-grained feldspar grains constituted feldspar-rich layers in the mylonite. The albitic plagioclase grains in the layers show a nearly random lattice preferred orientation (Fig. 7). The intergranular spaces between the fine-grained plagioclases filled by interstitial K-feldspar tend to be at a high angle to the mylonitic foliation, resembling grain boundary voids filled by vapor phase (thus fluid) of octachloropropane in polycrystals of octachloropropane deforming dominantly by grain boundary sliding (Rec, 1994, 2000). Kruse and Stünitz (1999) also reported similar microstructures in which hornblende grains nucleated at dilatant sites between plagioclase grains deformed dominantly by granular flow in anorthositic mylonites. All these microfabrics of the feldspar-rich layers in the mylonite indicate that feldspar grains were deformed dominantly by granular flow in anorthositic mylonites. Although minor fracturing still occurred in the layers.

With the development of compositional layering and the dominant granular flow of feldspar-rich layers in the mylonite, it is expected that the strain would be more distributed in the thin-section scale, resulting in a lower stress and/or lower strain rate in quartz-rich layer of the mylonite relative to that of the protomylonite. The lower stress led to the larger grain size of recrystallized quartz in the mylonite than that in the protomylonite.

5. Conclusions

1. A significant grain-size reduction of feldspar occurred due to fracturing, myrmekite formation and neocrystallization of albitic plagioclase along the shear fractures of K-feldspar porphyro-
oclasts in granitic mylonites of the Yecheon shear zone deformed under middle greenschist-facies conditions.

2. Neocrystallization of albitic plagioclase along the shear fractures of K-feldspar porphyroclasts was induced by both strain energy adjacent to the shear fractures and chemical free energy due to the compositional disequilibrium between Na-rich fluid and host K-feldspars.

3. As the deformation proceeded, compositional layering consisting of feldspar-, quartz- and muscovite-rich layers developed in the mylonite. The feldspar-rich layers, composed of fine-grained albitic plagioclase and interstitial K-feldspar, were deformed dominantly by granular flow, while the quartz-rich layers were deformed by dislocation creep.

4. With the layer development in the mylonite, strain was more distributed among the layers, resulting in a lower stress and/or lower strain rate in the quartz-rich layers of the mylonite compared to those of protomylonite. This led to a larger grain size of recrystallized quartz in the mylonite than that in the protomylonite.

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