Intergranular tensile microfractures within a mylonitized Ryoke granite: evidence for post-mylonitic deformation at the ductile-to-brittle transition

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Received August 31, 1995.
Accepted February 8, 1996.
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Abstract

Microstructural analyses have revealed three stages of microfracturing within a mylonitized Ryoke granite along the Median Tectonic Line, central Japan. Intragrannular microfracturing occurred in feldspar porphyroclasts during mylonitization associating with development of the Kashio shear zone. Subsequently, intergranular tensile microfractures, which are defined by fluid inclusion planes in the quartz matrix and chlorite-quartz veinlets in feldspar porphyroclasts, cut the pre-existing mylonitic fabrics. Dynamic recrystallization occurred locally within the vein-filling quartz. These features suggest that the intergranular tensile microfracturing took place as a result of hydraulic fracturing in the ductile-to-brittle transition field after mylonitization. Their structural trends indicate that this fracturing occurred under a different stress field from that for the mylonitization. Younger calcite veining occurred in close conjunction with the cataclastic movement along the Median Tectonic Line at shallower levels.

Key words: intragranular and intergranular fracturing, mylonite, cataclasite, fluid inclusion plane, Kashio shear zone, Median Tectonic Line, Ryoke belt, the ductile-to-brittle transition

Introduction

Mylonite is often regarded as a typical example of deformed rocks in the ductile regime (e.g., Bell and Etheridge, 1973; Berthé et al., 1979; Michibayashi and Masuda, 1993). However, mylonite itself could be also fractured at shallower depth during exhumation, so that such a mylonite preserves younger deformation events after mylonitization. Hence, detailed observations of microstructures within mylonite are important not only to study ductile shear deformation but also to reveal structural histories of rock bodies from the ductile to brittle regimes. In this paper, I show three stages of microfracturings within a mylonitized granite in the Kashio shear zone, the Chubu district, Japan, and discuss their timing during exhumation along the Median Tectonic Line. Although these microfractures have often been ignored or regarded to be insignificant fabrics, they may contribute to understanding structural evolution of the Median Tectonic Line.

Geological setting

The granite described here was obtained from the Kashio shear zone (Fig. 1; e.g., Hara et al., 1980; Takagi, 1984, 1986; Michibayashi and Masuda, 1993; Ohtomo, 1993; Yamamoto, 1994) within the Ryoke metamorphic belt in the Chubu district. This shear zone develops within the southeastern margin of the Cretaceous plutonic complex that intrudes the Ryoke high temperature/low pressure metamorphic rocks (e.g., Ryoke Research Group, 1972) along the N-S trending Median Tectonic Line. The shear zone developed during the Late Cretaceous-Early Tertiary (Hayama and Yamada, 1980; Shibata and Takagi, 1988; Dallmeyer and Takasu, 1992; Ohtomo, 1993). A kinematic study shows that deformation within the shear zone contained pure shear and simple shear components as $0^\circ < \Theta < 40^\circ$, where $\Theta$ is a kinematic index angle to state the degree of non-coaxiality (Masuda et al., 1995).

Microstructural studies of the Kashio shear zone show that the feldspars were plastically deformed at amphibolite facies metamorphic conditions, resulting in dynamic recrystallization along grain boundaries and replacement by myrmekite from the rim to the core in K-feldspar porphyroclasts (e.g., Takagi, 1986; Michibayashi and Masuda, 1993; cf. Yamagishi and...
Kanagawa, 1994). Mylonitic fabrics such as S-C fabrics (e.g., Berthé et al., 1979) and asymmetric strain shadows (e.g., Simpson and Schmid, 1983) also are well developed, indicating a regional sinistral strike-slip or top-to-the-south sense of shear (e.g., Takagi, 1986; Yamamoto and Masuda, 1990; Michibayashi and Masuda, 1993; Yamamoto, 1994).

Michibayashi and Masuda (1993) discussed that progressive retrogression led to strain localization during shearing, such that only a narrower zone of approximately 400 m in width along the margins of the plutons was further deformed during later stage of mylonitization. Furthermore, this zone appears to develop a steady-state grain size (cf. Twiss, 1977; Etheridge and Wilkie, 1979) of approximately 40 μm in dynamically recrystallized quartz aggregates (Michibayashi, 1993). Recently, Nakashima et al. (1995) demonstrated that the mylonitized granite showed an increase in water content in quartz grains from approximately 300 ppm to 2500 ppm towards the Median Tectonic Line, being consistent with the decrease of the mean grain size of quartz within the granites (see also Yamagishi et al., 1994, 1995).

The sample reported in this paper is a mylonitized hornblende-biotite granite collected from Yanazawa Creek (i.e. YG8 in Fig. 2b of Michibayashi and Masuda, 1993), where is located at approximately 800 m from the Median Tectonic Line. The mylonitic foliation there strikes 020° and dips approximately 50° NW. The foliation surfaces contain distinct mineral stretching lineations trending 010° and plunging shallowly to the north. Microfractures described here were observed in a thin section perpendicular to the foliations and parallel to the lineations (Fig. 2).

Three stages of microfractures

Microfractures were morphologically classified into two types (e.g., Engelder, 1987): intragranular micro-
Fig. 2. A macroscopic view of microstructures studied in this paper. Open polar. Width of base, 2 cm. A zone of intergranular tensile microfracturing, bounded by two thick broken lines, cutting mylonitic fabrics by a high angle. Locations of subsequent figures are shown by thin broken boxes.
fractures (cracks cutting within one grain) and intergranular microfractures (cracks cutting more than one grain). Three stages of microfracturing were recognized within the mylonitized granite as follows.

1. Syn-mylonitic intragranular microfractures (the first stage fracturing)

Intragranular microfractures occur dominantly in plagioclase and K-feldspar porphyroclasts (mean grain size: ca. 750 μm) and locally in amphiboles with quartz infills in the fine-grained matrix (Fig. 3). Since these microfractures were well documented by Michibayashi (1996), they are only briefly presented in this section. The fracture surfaces are very sharp and a few syntaxial overgrowth occur locally along the rims of the fractured feldspar porphyroclasts (Fig. 3a). Segments of fractured porphyroclasts are pulled

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**Fig. 3.** (a) Intragranular microfracture in an "augen" K-feldspar porphyroclast. The fracture at the centre of this grain contains dynamically recrystallized quartz infill, where syntaxial growth of K-feldspar occurs along the fracture walls. A number of the cleavage-parallel microfractures are present plus a fracture along a twin boundary. Younger extensional shear fracturing cut this porphyroclast with calcite infills (Cc with an arrow). Cross polars. Width of base, 16 mm. (b) "V"-shape intragranular microfractures in a plagioclase porphyroclast. The fracture spaces are filled with quartz and fluorite (F), Quartz-chlorite veinlets (arrows) resulting from intergranular tensile microfracturing. Width of base, 5 mm. The location of Fig. 7b is shown in a box.

**Fig. 4.** (a) Fluid inclusion planes (e.g., arrows). Open polar. Width of base, 100 μm. (b) Cross polar. Grain boundaries of quartz show no displacement along the fluid inclusion planes. Width of base, 100 μm.

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**Fig. 5.** (a) Trends of the syn-mylonitic intragranular microfractures with respect to the shear plane. (b) Trends of the intergranular tensile microfractures with respect to the shear plane.
apart and/or displaced in the fine-grained matrix. Separation distances are 1000μm in maximum. The quartz infills have been dynamically recrystallized (Fig. 3a). Frequently, the intragranular microfractures follow cleavages in both plagioclase and K-feldspar. Their twin boundaries have also parted and contain quartz infills. Locally, fluorite forms with quartz in the gaps between fractured segments (Fig. 3b).

2. Fluid inclusion planes in quartz and quartz-chlorite veinlets in feldspar (the second stage fracturing)

Fluid inclusion planes, which consist of thin planar trails of numerous minute (≤ca. 10μm) fluid inclusions (Fig. 4), occur in a narrow zone of approximately 1 cm in width within this granite (Fig. 2) and align independently of the crystallographic orientation of quartz. The fluid inclusion planes trend oblique to the syn-mylonitic intragranular microfractures and lie 120° to 150° anticlockwise from the shear plane (Fig. 5).

In contrast, quartz-chlorite veinlets occur in feldspar porphyroclasts in this narrow zone and have similar trends with those of the fluid inclusion planes (Fig. 6). Moreover, seams of fluid inclusion trails occur even within the quartz infills of the syn-mylonitic intragranular microfractures in these porphyroclasts (Fig. 7). These show that the quartz-chlorite veinlets in feldspar porphyroclasts occurred simultaneously with the formation of the fluid inclusion planes in quartz. That is, intergranular microfracturing within this granite resulted in various microstructural developments: the formation of fluid inclusion planes in quartz correlating with quartz-chlorite veining in feldspar, as the former are common indicators of healed microcracks (Fig. 2; e.g., Smith and Evans, 1984; Engelder, 1987).

The fluid inclusion planes cut across dynamically recrystallized quartz aggregates (Figs. 4 and 6). However, there is no evidence of grain boundary offset along the fluid inclusion planes in quartz (Figs. 4 and 6), suggesting that the intergranular microfracturing was not accompanied by shearing, but was purely extensional. Quartz grains in the veinlets were very locally recrystallized into fine grains (Fig. 8). However, the fluid inclusion planes are not overprinted by intragranular plastic deformation in the fine-grained quartz matrix (Figs. 3 and 6).
3. Calcite veins (the third stage fracturing)

Calcite veins, mostly less than 50 μm in width, occur preferentially in the zone of the fluid inclusion planes. The calcite veins occur rather irregularly and sporadically by replacing the pre-existing microstructures including the fluid inclusion planes and the quartz-chlorite veinlets as well as the mylonitic fabrics within this granite. Some calcite veins, however, occur locally as a result of extensional shear microfracturing (Figs. 3a and 8), but separations are estimated to be less than 100 μm.

Discussion: Timing of three stage microfracturing

The mylonitized granite in this study preserves at least three distinctive microfractures formed in three stages: the syn-mylonitic intragranular microfractures (1st stage) in the feldspar porphyroclasts, the intergranular tensile microfractures (2nd stage) occurring as the fluid inclusion planes in quartz and the quartz-chlorite veinlets in feldspar, and the calcite veins resulting from extensional shearing (3rd stage). The 1st stage microfractures in feldspar porphyroclasts occurred genuinely when this granitic body was in the ductile regime (Michibayashi, 1993, 1996; Michibayashi and Masuda, 1993). Michibayashi (1996) suggested that the intragranular microfracturing during the mylonitization was statistically explained in terms of a fibre-loading model: the tensile stress exceeds the tensile fracture strength of the grain during stress transfer (e.g., Lloyd et al., 1982; Masuda et al., 1989; Ji and Zhao, 1993). Furthermore, the existence of fluorite within gaps between fractured segments (Fig. 3b) indicates that the separation of the segments occurred simultaneously with the dissolution-precipitation process during the mylonitization (e.g., Lloyd and Knipe, 1992; Hippertt, 1993). Also, it suggests that hydrothermal alteration had already taken place during the mylonitization.

The subsequent overprint of the mylonitic fabrics by the 2nd stage microfracturing resulted in the development of the fluid inclusion planes in quartz and the quartz-chlorite veinlets in feldspar porphyroclasts (e.g., Fig. 6). The fluid inclusion planes are common indicators of healed microcracks (e.g., Smith and Evans, 1984; Engelder, 1987; Takeshita, 1995). Smith and Evans (1984) suggested that cracks will heal rapidly compared to geological time scales at temperatures ≥ ca. 300°C (e.g., Tullis and Yund, 1977).

Lespinasse and Pècher (1986) showed that a set of fluid inclusion trails related to one stress field is essentially unaffected by the geometry of previously formed trails or structures, even though the pre-existing geometry resulted from deformation under differentially oriented stress field. Therefore, the different trend of the fluid inclusion planes from that of the mylonitic fabrics (Fig. 5) indicates that the intergranular tensile microfracturing at this stage developed under a different stress field from that for the mylonitization (cf. Babaie et al., 1991; Jang and Wang, 1991).

Consequently, it suggests that the 2nd stage microfracturing occurred at least in the ductile-to-brittle transition regime under a different stress field after the mylonitization. This means that this granitic body moved to another tectonic environment after the development of the Kashio shear zone.

The calcite veins cut the 2nd stage microfractures (Fig. 8). These calcite veins seem to be identical to those described by Takagi (1983). Takagi (1983) characterized the microstructures resulting from cataclastic deformation on previously mylonitized quartz-dioritic gneiss along the Median Tectonic Line. As a result, cataclastic fabrics were classified into four types: A-type (uncrushed rocks), B-type
(slightly crushed rocks with fracturing and veining), C-type (partially crushed rocks with zones of granulation and/or comminution), and D-type (pervasively crushed rocks, namely, cataclasite or microbreccia). Since most of the C- and D-type rocks occur in about 300 m to the Median Tectonic Line, Takagi (1983) argued that the cataclasism developed during activity of this major fault zone at shallower levels (see also Echigo and Kimura, 1973; Yoshida and Masaoka, 1973). The mylonitized granite in this study may be classified as A or B type of Takagi (1983). Therefore, the calcite veining within the granite could result from weak cataclastic deformation associating with the movement of the Median Tectonic Line in the brittle regime.

In summary, the three stage microfracturing occurred within this mylonitized granite as the granitic body was uplifted from the ductile to the brittle regime as illustrated in Fig. 9. This microstructural evolution can be constrained in the isochronological data of Tagami et al. (1988) and Dallmeyer and Takasu (1992). Dallmeyer and Takasu (1992) suggested that mineral ages preserved within the Ryoke granites could reflect two stages of relatively rapid cooling: one between 500 and 300°C during 70-66 Ma (Late Cretaceous; Maastrichtian), and the other between 250 and 100°C during 58-54 Ma (Early Eocene). Accordingly, Michibayashi and Masuda (1993) interpreted that the mylonitization developed by the rapid cooling event at approximately 62-63 Ma. However, the present study showed that the 2nd stage microfracturing occurred in the ductile-to-brittle transition after the mylonitization. Therefore, it suggests that the ages of 62-63 Ma may be related to the 2nd stage microfracturing, so that this microfracturing event occurred just before or during the earlier stage of the rapid cooling event from 250°C to 100°C.

However, the tectonic environment of the 2nd stage microfracturing is ambiguous. Since the calcite veins occur preferentially in the zone of the fluid inclusion planes, the intergranular tensile microfracturing at this stage may be part of cataclasism at
the deeper level, associating with the present Median Tectonic Line (cf. Takagi, 1983). Alternatively, its development may occur before the cataclasis. Yamamoto and Masuda (1990) revealed that the Kashiio shear zone is folded with a vertical fold plane in the vicinity of Misakubo; the trend of the fold axis is oblique to the strike of the Median Tectonic Line. Ohtomo (1993) interpreted that the upright folds were developed as echeon folds with a left-lateral strike-slip component related to the high-angle Median Tectonic Line (see also Hara et al., 1977, 1980). Although the development of this upright folding is not yet clearly known, I prefer that the 2nd stage microfracturing may be related to the stage of upright folding during the uplift of the Kashiio shear zone. As the 2nd stage microfracturing occurred before or during earlier stage of the rapid cooling event as described above, the upright folding may have significant role on uplifting of the Kashiio shear zone.

Nonetheless, as the hydrothermal alteration had already began within this granite during the mylonitization, it is likely that fluid phases existed sufficiently within this rock body even after the mylonitization. Therefore, the 2nd stage microfracturing would result from elevation of high fluid pressure to cause the extensional stress within the granite (e.g., Etheridge, 1983; Takeshita, 1995). This means that hydraulic fracturing occurred within this granite in the ductile-to-brittle transition regime (cf. O’Hara, 1990; Bailey, 1990; Nakashima, 1995).

It is, however, stressed that these hypotheses should be tested on a regional scale. Also, chemical analysis, measurement of homogenization temperature and isotope dating of fluid inclusions are required to reveal more precise timing of the intergranular fracturing during the uplift of the Kashiio shear zone, in conjunction with the development of the Median Tectonic Line.

Acknowledgments
The author acknowledges Toru Takeshita, Kazuhiko Ishii, Hideo Takagi, Ken-ichi Kano and the colleagues of Yuruyuru for the valuable comments and discussions, and Tim Bell and Ken-ichi Kano for improving the English in this paper. A part of this paper was financially supported by an Overseas Postgraduate Research Scholarship, a James Cook University Postgraduate Research Scholarship and Grant-in-Aids for Scientific Research from the Ministry of Education, Science and Culture, Japan.

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長野県下伊那郡上村地域の中央構造線沿いに露出する花崗岩に、3種類の微小割れ目が亜延性領域からの上昇の過程で重複して発達した。最初に巣間断層帯の発達によるマイロナイト化に伴って塑性流動がした石英質中の長石ポフィロックラストに粒内割れ目が形成された。次に、これらマイロナイトの組織を切断して粒間張裂れ目が形成された。この粒間張裂れ目は石英中の流れ体流動の特有な粒内割れ目であるが、長石ポフィロックラスト中では石英の錠結晶により充填された細粒である。この細粒の石英には流動滑片と細粒化組織が認められ、粗状点状から推察される最小変形応力軸がマイロナイト形成時の応力場とは斜交する。したがって、粒間張裂れ目は延性-脆性変形領域における構造変動の影響を受けて水圧破壊が起こったことを示唆している。最後にカップラサイト帯に発達する方解石脈が、これらの組織をさらに切断し変化した。