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Shearing during progressive retrogression in granitoids: abrupt grain size reduction of quartz at the plastic–brittle transition for feldspar

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Abstract—The Kashio shear zone, Chubu district, Japan, affects the southeast margins of the Ryoke granitic plutons as well as the Ryoke metasedimentary rocks, and is truncated by the Median Tectonic Line near the shear zone centre. Coarse quartz grains within the granitic rocks have been dynamically recrystallized to quartz aggregates towards the pluton margins. The grain size data show an abrupt reduction from various sizes (59–148 μm) to a steady-state size around 35 μm at approximately 400 m from the boundary of the granitic plutons without any tectonic boundary such as a fault being present. This abrupt grain size reduction accompanies brittle deformation in feldspar that overprints earlier plastic deformation and develops strong mylonitic fabrics. In contrast, feldspar away from the pluton margins contains only weak microstructural evidence for plastic deformation and still locally preserves magmatic polycrystal structures amongst the inhomogeneously recrystallized quartz grains.

These features, combined with an isochronological study, suggest that the Kashio shear zone began at high temperature (≥450°C) as a ductile event that affected relatively wide regions in the Ryoke granitic plutons before rapid cooling by *ca* 70 Ma. At this latter stage, strong mylonitization at lower temperatures (≥300°C) in a semi-ductile regime occurred in a narrow zone towards the shear zone centre. Here, recrystallized quartz aggregates reached a steady-state grain size by *ca* 60 Ma. That is, cooling within the granitic plutons resulted in strain localization, with the abrupt grain size reduction of quartz aggregates correlating with the plastic–brittle transition of feldspar.

INTRODUCTION

THE Median Tectonic Line (Fig. 1) is a major, polyphase, transcurrent fault, which lies between the Ryoke high temperature–low pressure and Sambagawa low temperature–high pressure metamorphic belts (e.g. Ichikawa 1980) that form part of the paired metamorphic belt of Miyashiro (1973). The Kashio shear zone (i.e. the Ryoke southern marginal shear zone of Hara *et al.* 1977, 1980) lies on the Ryoke metamorphic belt side along this major fault (Figs. 1 and 2). Mylonitic fabrics within the margin of the granitic plutons have been well documented. These include dynamic recrystallization of quartz (Hara *et al.* 1977, 1980, Takagi 1984, 1986, Hayashi & Takagi 1987, Takagi & Ito 1988, Yamamoto in preparation), grain size reduction of feldspar (Echigo & Kimura 1973), development of asymmetric fabrics around feldspar porphyroclasts (Takagi 1984, 1986, Takagi & Ito 1988, Yamamoto & Masuda 1990, Masuda *et al.* in preparation) and development of shear bands (Takagi 1992).

Grain size reduction is characteristic of shear zone development (e.g. Bell & Etheridge 1973, 1976, White 1973, 1976, 1977, 1979, Twiss 1977, Etheridge & Wilkie 1979, 1981, Tullis *et al.* 1982). Consequently, reduction in grain size in recrystallized quartz aggregates across the Kashio shear zone was commonly used to demonstrate that this zone existed (e.g. Hara *et al.* 1980, Takagi 1986, Hayashi & Takagi 1987, Takagi & Ito 1988). However, these data reveal that the grain size reduction occurs abruptly in close proximity to the Median Tectonic Line. This abrupt grain size reduction in recrystallized quartz aggregates commonly occurs within the margins of the Ryoke granitic plutons along the Median Tectonic Line from Ichinose in the north (e.g. Takagi 1986) to Sakuma in the south (e.g. Ohtomo 1988), although no structural discontinuity, such as a fault, has been reported at the outcrop scale (e.g. see Takagi 1986).

These granitic rocks also contain feldspar porphyroclasts towards the shear zone centre (e.g. Takagi 1986, Takagi & Ito 1988). Both feldspar and quartz microstructures within natural shear zones have been the focus of much research in natural occurrences (e.g. White 1975, Allison *et al.* 1979, Berthé *et al.* 1979, Borge & White 1980, Hanmer 1982, Watt & Williams 1983, Simpson & Schmid 1983, Vernon *et al.* 1983, Jensen 1985, Passchier & Simpson 1986, White & Mawer 1988, Bell & Johnson 1989, Ji & Mainprice 1980, Gower & Simpson 1992), and have also been investigated in laboratory experiments (e.g. Tullis & Yund 1977, 1980, 1985, 1987, 1991, Marshall & McLaren 1977a,b,c, Willaime *et al.* 1979, Tullis 1983, Dell'Angelo & Tullis 1989). It is generally accepted that the plastic–brittle

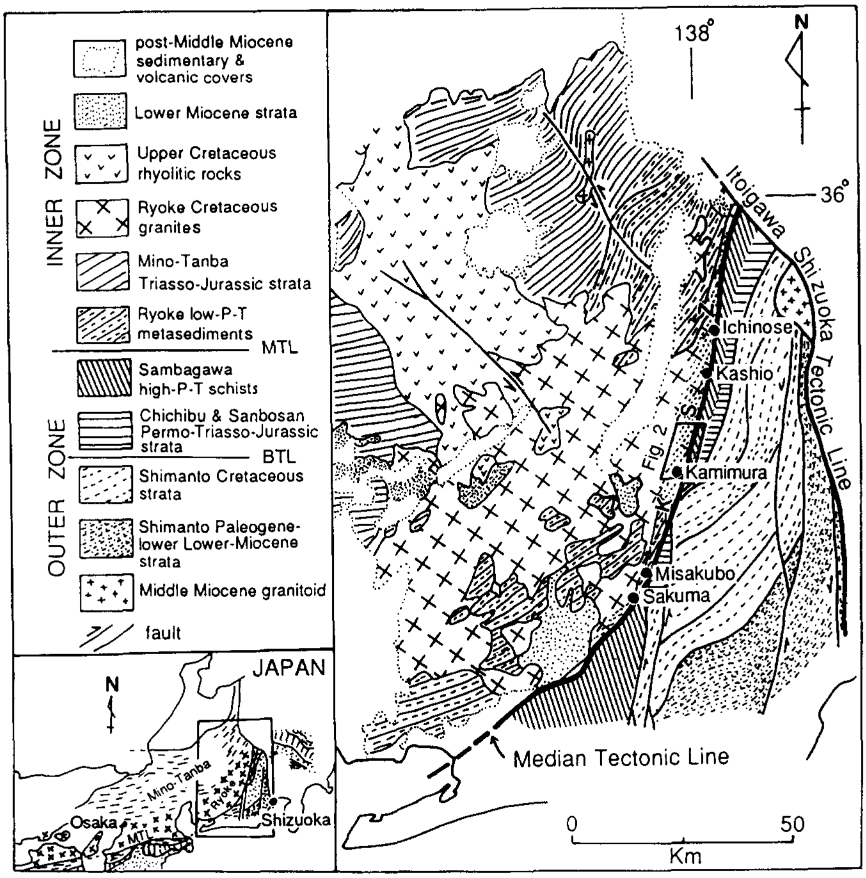


Fig. 1. Geological map of the Chubu district, Japan (after Kano *et al.* 1990). MTL, Median Tectonic Line; BTL, Butsuzo Tectonic Line. The Kashio shear zone in the main figure is on the western side of the Median Tectonic Line, labelled KSZ. Location of Fig. 2 is shown.

transition for feldspar occurs at higher-temperature conditions than for quartz (e.g. Tullis & Yund 1977, Simpson 1985, Gapais 1989). Therefore, it is quite possible to interpret relative deformation conditions, particularly with respect to thermal history, based on feldspar microstructures as well as quartz microstructures (e.g. Gapais 1989, Gates & Glover 1989).

This paper firstly summarizes arguments about the relationship between the Kashio shear zone and the Median Tectonic Line, and then reviews a macroscopic movement picture for this shear zone in the vicinity of Kamimura (Fig. 2) where little work has been previously conducted. The microstructures along Yanazawa Creek, which shows a natural cross-section of the shear zone in this vicinity (Fig. 2), are then interpreted in detail. An extreme reduction in the grain size within quartz aggregates occurs within the granitic rocks along Yanazawa Creek, and the data obtained from this location are examined and discussed in relationship to the accompanying microstructures that develop in feldspar.

GEOLOGICAL SETTING

The Kashio shear zone occurs along the Median Tectonic Line and is truncated along its shear zone centre by this regional fault (Fig. 2). No equivalent shear zone has been found on the Sambagawa belt side of the Median Tectonic Line (e.g. Takagi 1986). To the west, mylonitic foliations of the shear zone grade into weak magmatic flow textures within Ryoke granitic plutons. For decades, it has been generally accepted that the Kashio shear zone was a strike-slip shear zone which accompanied the Median Tectonic Line in the Ryoke metamorphic belt (e.g. Takagi 1986). Because of a minor amount of vertical-slip, the 'eastern part' of the shear zone appears to be truncated during the exhumation along this major fault as well as that of the Ryoke metamorphic rocks (e.g. Takagi 1986).

Recently, a number of preliminary studies have shown that the Kashio shear zone in Chubu district changes in dip from vertical to subhorizontal, and is then truncated by the Median Tectonic Line between Kamimura and Sakuma (Yamamoto & Masuda 1987, 1990, Ohtomo 1987, 1988, Michibayashi & Masuda 1988, Masuda *et al.* 1990). In the vicinity of Misakubo (Fig. 1) the shear zone is sub-horizontal, and mylonitic foliations form a macroscopic antiform that is truncated on the eastern limb by the Median Tectonic Line (Yamamoto & Masuda 1990). Therefore, the structural relationship between the Kashio shear zone and the Median Tectonic Line appears to be not as simple as in the vicinity of Takato, and the shear zone may have been cut by this major fault during later tectonic activity in southwest Japan. Consequently, the shear zone should be re-evaluated in detail before its relationship with the Median Tectonic Line is discussed. In this paper, we focus only on the development of the Kashio shear zone.

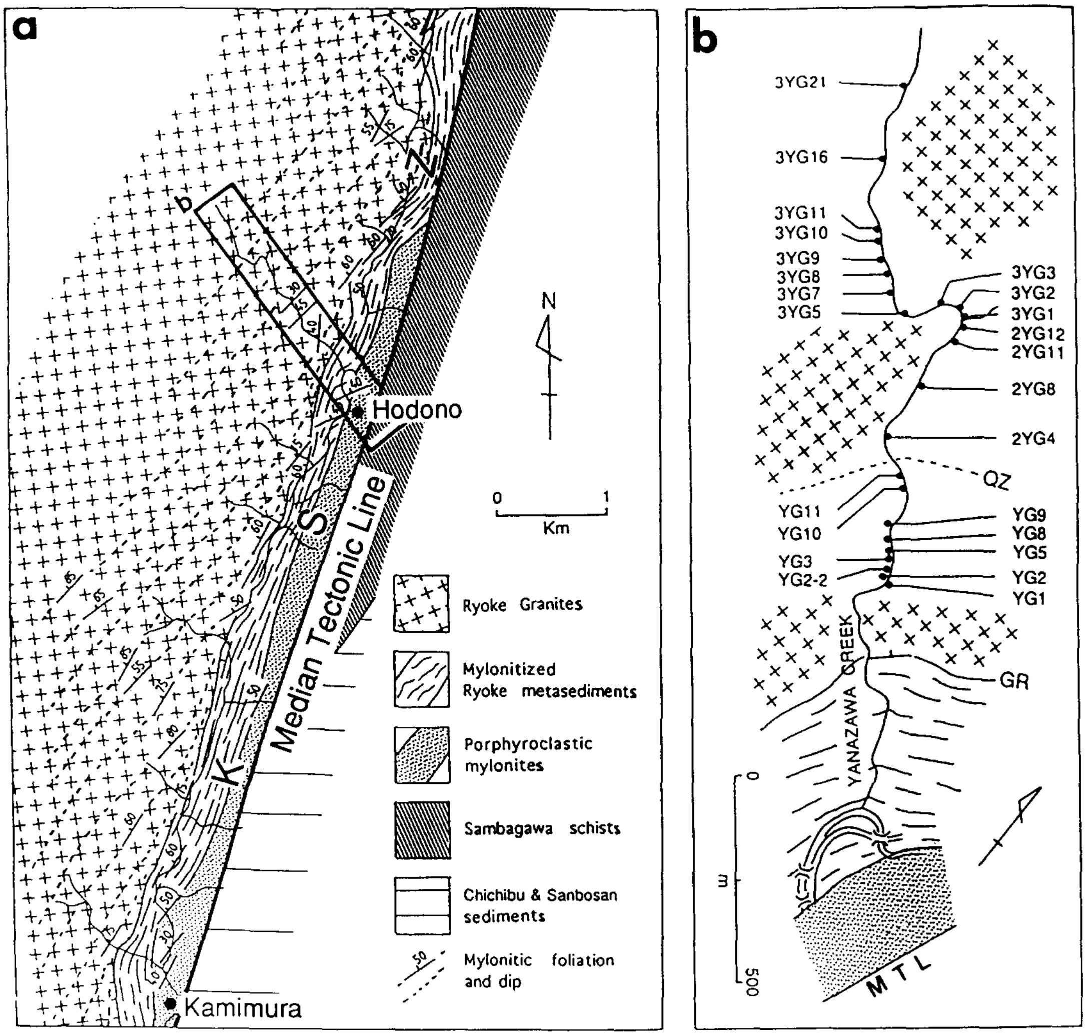


Fig. 2. (a) Geological map in the vicinity of Kamimura. Macroscopic gneissose and mylonitic foliations are traced within the Ryoke granitic rocks. The Kashio shear zone is labelled KSZ. (b) Sample localities along Yanazawa Creek. Sample numbers are used in subsequent figures.

The Kashio shear zone in the vicinity of Kamimura

Three distinct rock types occur within the Kashio shear zone: granitoids, metasediments and porphyroclastic mylonites (Fig. 2). The granitoid rocks form a part of the Ryoke granitic plutons (e.g. Hayama & Yamada 1980) and are classified into Older Granitic Rocks (e.g. Nozawa 1983). Mesoscopic gneissose foliation occurs within these rocks, striking 040° and dipping subvertically; it is not accompanied by solid-state deformation microstructures (Fig. 2a). This foliation transforms into a mylonitic foliation towards the southeast margin of the Ryoke granitic plutons where the shear zone occurs. The mylonitic foliation (S_m) within the granitoids strikes from 040° to 020° and dips more shallowly (approximately 50°NW) towards the margin of the plutons where S_m is subparallel to the foliation in the metasedimentary rocks (Fig. 2a). Samples in this study were collected from these granitoids along Yanazawa Creek in a cross-sectional traverse of the shear zone (Fig. 2b).

Mylonitized metasedimentary rocks occurring between the porphyroclastic mylonites and the granitoid rocks (Fig. 2), consist of metacherts, metapsammites and metapelites with local andalusite porphyroblasts. The mylonitic foliation (S_m) is commonly developed parallel to compositional layering, and strikes approximately 020°, with a variable vertical to shallow (30°NW) dip (Fig. 2a). The thin (commonly 5 – 30 cm) quartzo-feldspathic dykes occur dominantly along the boundary with the granitic plutons, and are also strongly deformed during the mylonitization. Masuda *et al.* (1990) demonstrated that metasedimentary rocks within the Kashio shear zone belong to the Ryoke metasedimentary rocks, based on microstructures and feldspar compositions along the Ushirokochi-gawa river in the vicinity of Misakubo. This indicates that the shear zone developed during or after the intrusion of granitic plutons into the Ryoke metamorphic rocks (see also Suwa 1973).

The porphyroclastic mylonites, originally called the Kashio gneiss (Harada 1890) or the Kashio mylonite, mainly occur near the Median Tectonic Line (Fig. 2). They are characterized by feldspar and amphibole porphyroclasts in a fine-grained matrix containing quartz and phyllosilicate aggregates, although these microstructures were locally destroyed by retrogressive alteration. The porphyroclastic mylonites could have been derived from the plutonic or metapsammitic rocks, or both (e.g. Hayama & Yamada 1980, Ono 1981).

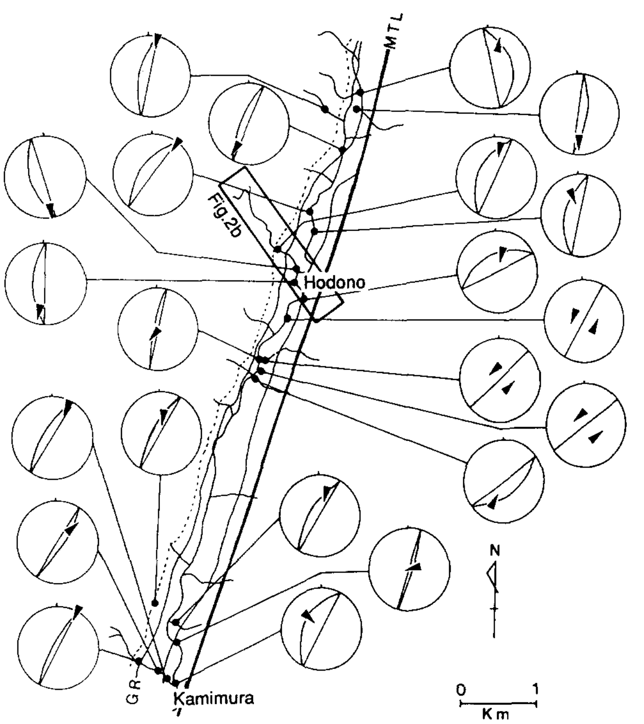


Fig. 3. Determined shear sense in the vicinity of Kamimura. Great circles in stereonets (lower-hemisphere projection) show foliation planes. Arrows at intersecting points of great circles indicate direction of shear movements of the hangingwall planes relative to the footwalls. Shear senses were determined based on combinations of two or more criteria (i.e. *S–C* foliations, asymmetric strain shadows around feldspar porphyroclasts, mica 'fish' and quartz shape-preferred orientations). GR, a boundary between the granitic pluton and the metasedimentary rocks. An approximate limit of the strongly mylonitized granitoids is shown within the Ryoke granitic pluton (the broken line).

S_m contains a strong mineral stretching lineation (L_m) trending 010° – 030° and plunging between 10° and 30°. On planes perpendicular to S_m and parallel to L_m, the *S–C* fabrics (cf. Berthé *et al.* 1979), asymmetric strain shadows around feldspar grains (cf. Simpson & Schmid 1983, Passchier & Simpson 1986, Takagi & Ito 1988) and/or mica 'fish' (cf. Lister & Snoke 1984) are strongly developed and indicate a regional sinistral strike-slip or top-to-the-south sense of shear (Fig. 3).

MICROSTRUCTURES IN THE RYOKE GRANITES

Microstructures of quartz aggregates

The grain size in quartz aggregates varies from coarse to fine across the Kashio shear zone. Coarse grains are dominant within the granites far away from the pluton margin. They show very irregular shapes with serrated grain boundaries (Figs. 4a–c). Although these granites have not developed mylonitic fabrics such as porphyroclasts with asymmetric shadows, dynamic recrystallization has occurred along or within the coarse quartz grains (Figs. 4a–c).

Mylonitic fabrics have developed towards the eastern margin of the granites. The coarse grains in quartz aggregates decrease in size and show an elongate shape commonly parallel to S_m, with strong undulose extinction, whereas the recrystallized grains increase in number and are much finer than those in the weakly deformed granites (Figs. 4d–f). Locally, where quartz aggregates are surrounded by non-porphyroclastic feldspars, their grain sizes are relatively coarser than those in the other aggregates (Fig. 4f).

Grain size distribution in quartz aggregate

A quartz aggregate containing the coarsest quartz grains was selected in each thin section. Careful sketches of grain boundaries of quartz aggregates were made with the help of photomicrographs, and subgrains were regarded as parts of the old grains. The sizes of the grains were then measured using a LUZEX image analyser (the method of Masuda *et al.* 1991). The size of a grain (di) was calculated as $di = 2\sqrt{(A/3.14)}$, where A is the area of the grain. Thus, grain size represents the diameter of a circle with the same area as that of the grain.

The grain size distributions at each site are shown in Fig. 6. The results show that each grain size distribution is approximately log-normal, particularly within samples near the granite margin. The relationship between the mean grain size and the distance from the Median Tectonic Line is shown in Fig. 7. The distance can be regarded as that from the shear zone centre, as it appears to be cut by the Median Tectonic Line. The mean grain sizes decrease towards the margin of the granitic plutons. However, the grain size reduction is not a gradual decrease, but instead, the mean grain size abruptly converges from a range of sizes to a very limited size across the boundary labelled QZ (Fig. 7). The mean grain size far from the margin (northwest side of QZ) ranges between 59 and 148 μm, whereas, those close to the margin (southeast side of QZ) range between 25 and 44 μm (Fig. 7). These data argue that the grain size reduction in quartz did not occur simply towards the margin of the granite plutons, but they show quite uniform mean grain sizes near the margin (cf. Takagi 1986, 1989). As discussed in a following section, this could result from development of a steady-state grain size (e.g. White 1976, Twiss 1977, Etheridge & Wilkie 1979) within this shear zone.

Microstructures of feldspar

Plagioclase grains in the Ryoke granites preserve evidence for both plastic and brittle deformation. Although the quartz has been recrystallized, the plagioclase grains in the weakly deformed granites are subeuhedral, and polycrystals are still preserved with little undulose extinction (Fig. 5a). This suggests that the total strain within these granites was quite low so that these feldspar polycrystals were prevented from separating into porphyroclasts (e.g. see figs. 10b & c of Bell & Johnson 1989). Recrystallization occurs very locally along grain boundaries, but no cracks or faults have

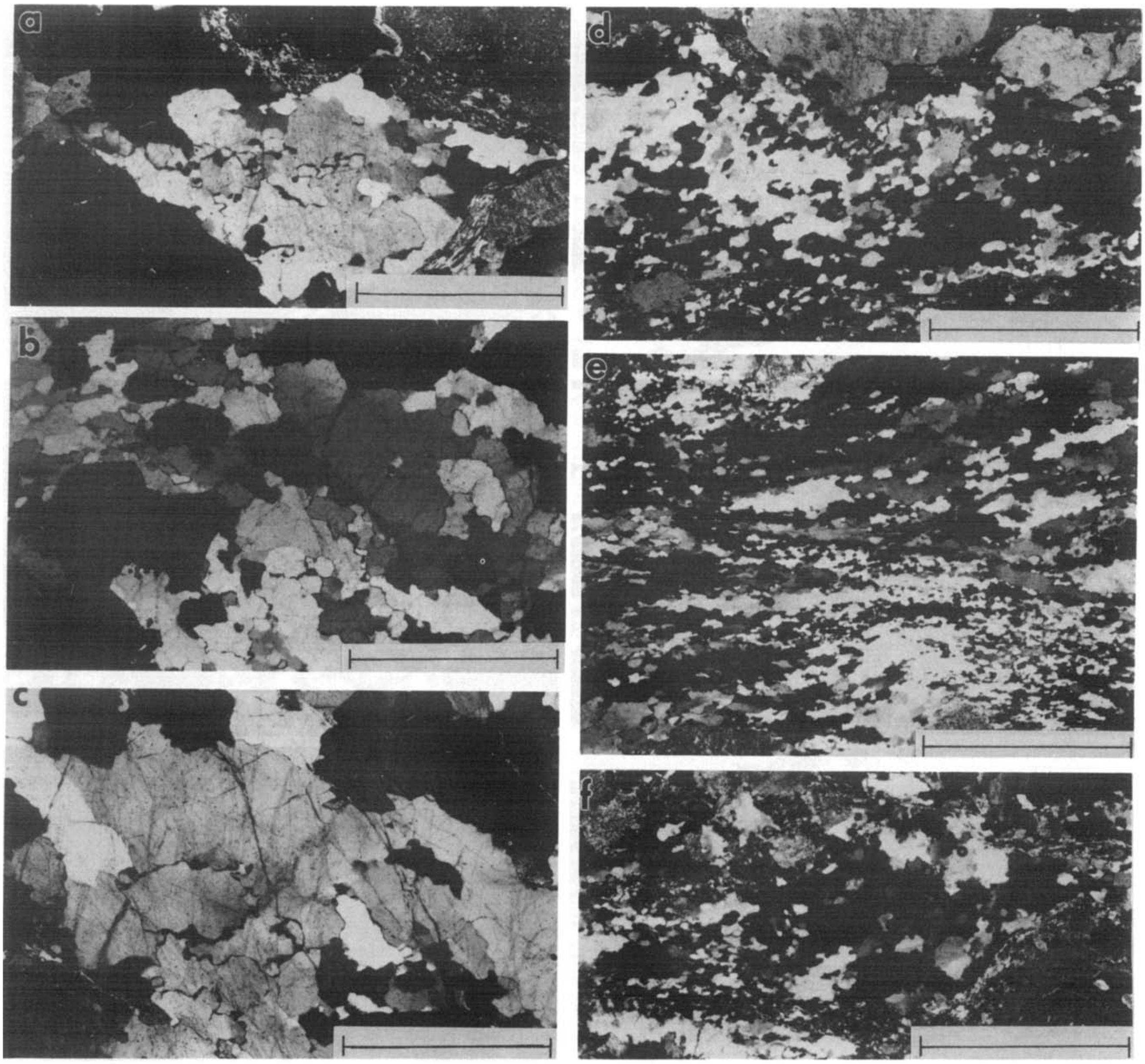


Fig. 4. Microstructures of both weakly and strongly recrystallized quartz aggregates within the granite pluton along Yanazawa Creek. Scale bars: 1 mm. Northwest side of QZ in Fig. 2(b): localities (a) 2YG4, (b) 2YG12 and (c) 3YG11. Recrystallization occurs within coarse grains with serrated grain boundaries although mylonitic foliation is weak or hardly recognized. Southeast side of QZ in Fig. 2(b): localities (d) YG1, (e) YG11 and (f) YG2-2. Strong recrystallization resulted in relatively uniform recrystallized grain sizes with some remnants of old grains parallel to S_m (E–W in photographs). These quartz aggregates show log-normal distributions with similar mean grain sizes.

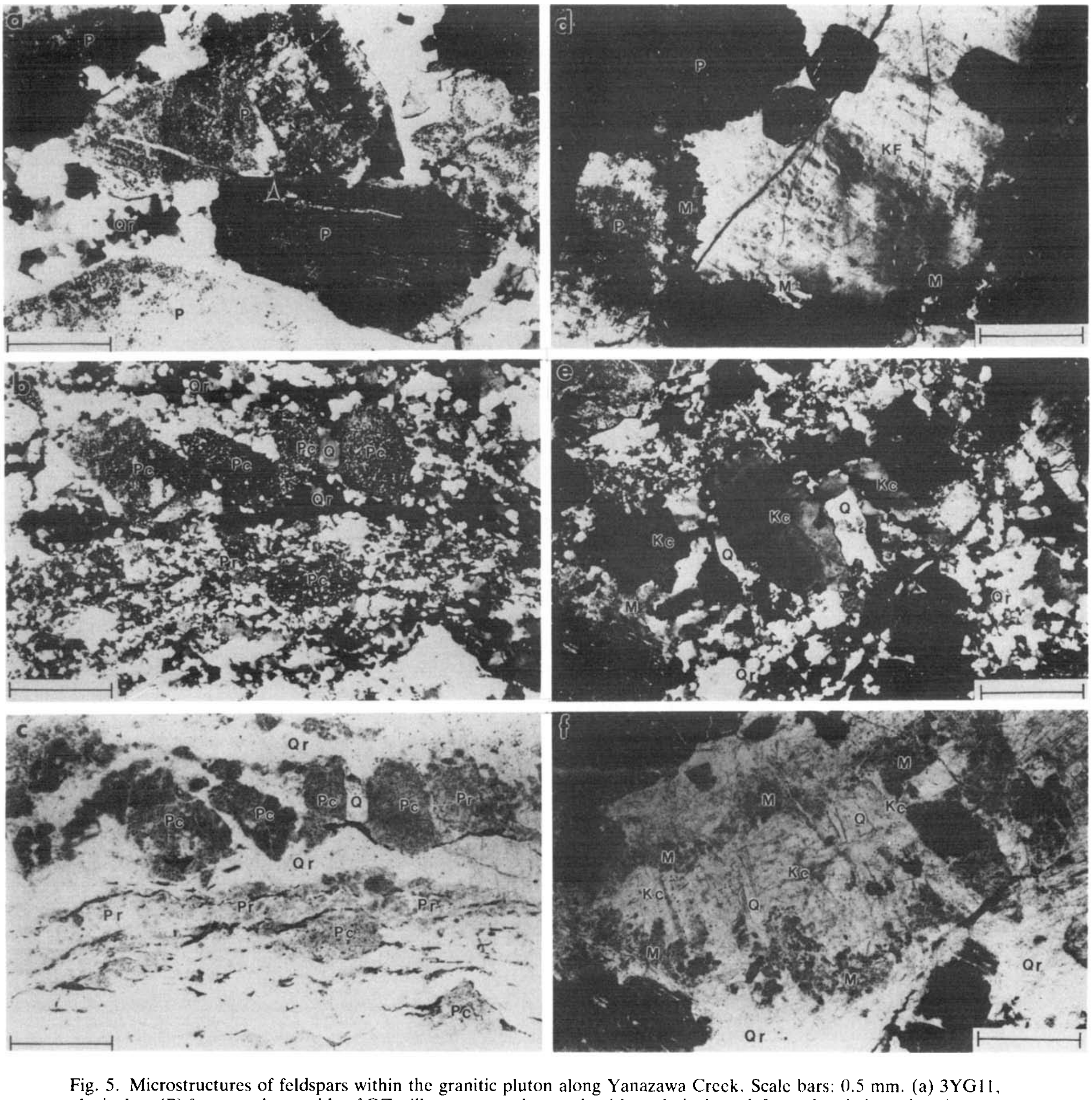


Fig. 5. Microstructures of feldspars within the granitic pluton along Yanazawa Creek. Scale bars: 0.5 mm. (a) 3YG11, plagioclase (P) from northwest side of QZ still occurs as polycrystals with a relatively undeformed grain boundary (arrow) despite quartz recrystallization (Qr). (b)&(c) YG2, plagioclase from southeast side of QZ occurs as both porphyroclasts (Pc) and recrystallized fine grains (Pr) in aggregates elongate parallel to S_m within recrystallized quartz grains (Qr). Porphyroclasts (Pc) resulted from a porphyroclast that was cracked and pull aparted with quartz infillings (Q). (d) 3YG7, K-feldspar (KF) from northwest side of QZ showing euhedral shape. Note that myrmekite (M) occurs along grain boundaries with plagioclase (P). (e)&(f) YG11, K-feldspar from southeast side of QZ occurs as a porphyroclast (Kc) that was cracked with quartz infillings (Q). Myrmekite (M) occurs around this porphyroclast.

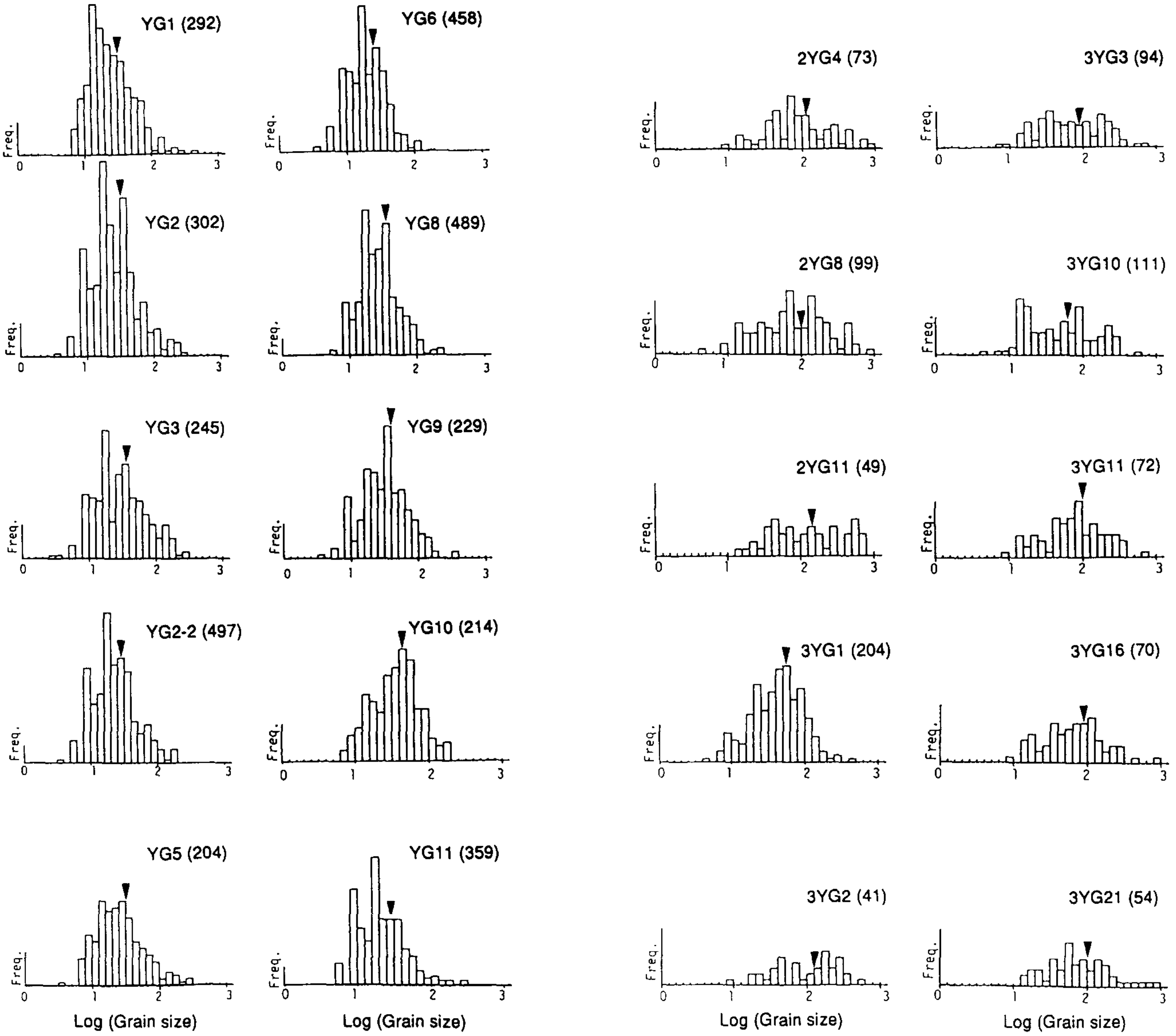


Fig. 6. Grain size distribution of recrystallized quartz aggregates along Yanazawa Creek. Sample localities are shown in Fig. 2(b). Numbers of grains measured are indicated in each bracket. Each arrow indicates the arithmetic mean grain size which is shown in Fig. 7. Distributions were determined from an approximately 3 × 2 mm^2 area containing the coarsest grains in each thin section. Towards the pluton margin, the distribution becomes log-normal with some skewness.

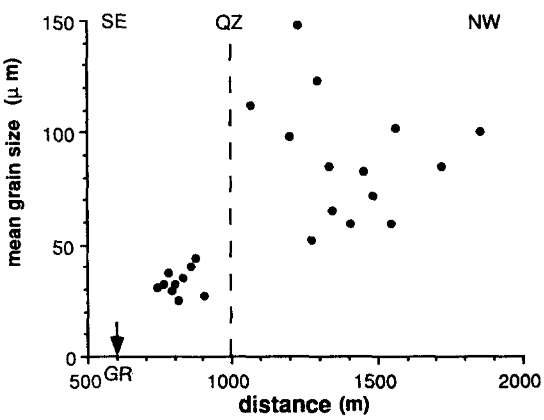
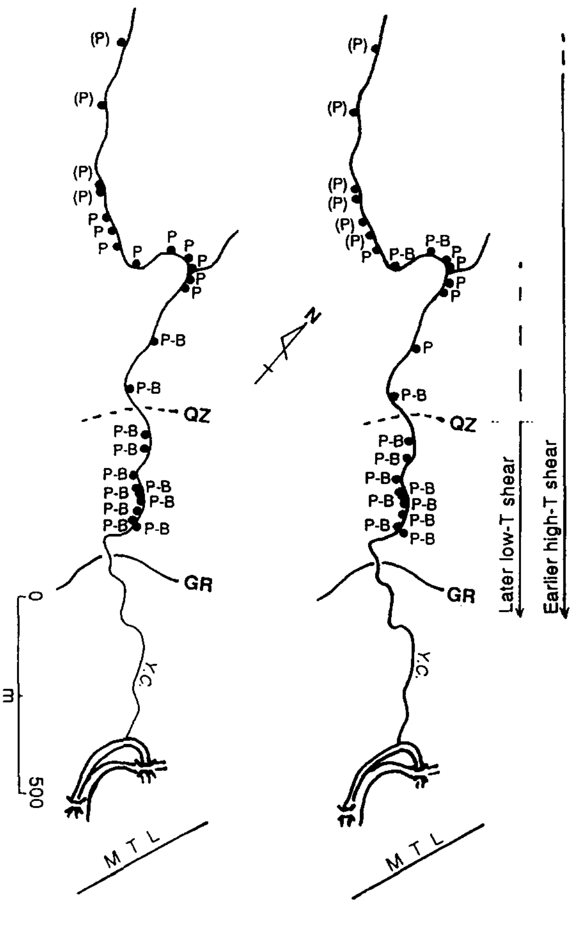


Fig. 7. Mean grain sizes (μm) of quartz aggregates within the granitic pluton along Yanazawa Creek vs the distance from the Median Tectonic Line. GR, boundary between the granitic pluton and Ryoke metasediments. QZ, boundary between inhomogeneously distributed mean grain sizes from 59 to 148 μm and relatively uniform mean grain sizes around 35 μm. The location of QZ was estimated on the basis of these data.

formed. Kink bands indicating low amounts of plastic deformation are locally present, but some plagioclase grains show no deformation microstructures.

In contrast, plagioclase grains in the mylonitic granites occur as porphyroclasts which contain evidence for brittle deformation such as cracks and faults (Figs. 5b & c). Undulose extinction is strong, and kink bands are common. Recrystallization occurs around porphyroclasts and commonly shows asymmetric geometries, indicating a sinistral or top-to-the-south shear sense. Some of these recrystallized grains form a compositional layering between quartz grains parallel to S_m (Fig. 5c).

K-feldspar also preserves both plastic and brittle deformation microstructures. In the weakly deformed granites, K-feldspar grains are anhedral and show perthite structures (Fig. 5d). Weak development of recrystallization occurs along grain boundaries, although myrmekite occurs predominantly along boundaries with plagioclase grains (Fig. 5d). In the mylonitic granites, K-feldspar



(a) plagioclase (b) K-feldspar

Fig. 8. Distribution of plastic–brittle deformation microstructures in feldspar. (P), weakly and slightly deformed plastically; P, moderately deformed plastically; and P–B: intensely deformed both plastically and brittlely. (a) Plagioclase, (b) K-feldspar. P–B distributions are well correlated with the zone of quartz recrystallization that shows relatively uniform mean grain sizes (southeast side of QZ). See text for discussion.

grains occur as porphyroclasts with strong undulose extinction, and are commonly cracked with quartz infills (Figs. 5e & f). Deformation bands are common. Small grains of plagioclase and/or myrmekite are present around K-feldspar porphyroclasts (Figs. 5e & f).

The distribution of plastic and brittle deformation features in feldspars is shown in Fig. 8: recrystallization in both feldspars, and myrmekite replacement in K-feldspar, are dominant features classified as P and (P), whereas cracks and microfaults with quartz infillings in both feldspars are denoted as B. Figure 8 clearly shows that plastic deformation is widespread along Yanazawa Creek although it is only weakly developed farther from the margin of the granite. In contrast, brittle deformation predominantly occurs near the margin of the granitic rocks.

INTERPRETATION AND DISCUSSION

Discontinuity in mean grain size of quartz aggregates across the shear zone

The discontinuity of quartz grain sizes shown in Fig. 7 for Yanazawa Creek also occurs within the other granites in the vicinity of Ichinose (Hara *et al.* 1980, Takagi 1986), Kashio (Hara *et al.* 1980, Hayashi & Takagi 1987, Takagi & Ito 1988) and Sakuma (Hara *et al.* 1980, Ohtomo 1988, Michibayashi & Masuda unpublished data). The grain size distributions in the vicinity of Ichinose show even more abrupt transitions than the data in this study (cf. Hara *et al.* 1980, Takagi 1986). Hara *et al.* (1980) regarded the narrow zone, where the recrystallized grain size decreases markedly, as a transition from weakly to strongly mylonitized rocks. The discontinuity of Takagi (1986) occurs between very closely spaced outcrops (i.e. less than several metres), although no structural discontinuity, such as a fault, could occur between them (see locations F and G shown in fig. 5 of Takagi 1986). Along Yanazawa Creek, there is no significant fault, either, suggesting that the discontinuity in the mean grain size of quartz aggregates did not result from subsequent tectonic movement. Thus, a major discontinuity in the mean grain size, that is not related to post mylonitic tectonic movement, appears to be common within the margins of the Ryoke granitic plutons along the Kashio shear zone.

Quartz aggregates within the weakly or undeformed Ryoke granites consist predominantly of coarse grains (>1 mm). During the development of the shear zone, and mylonitization, these coarse quartz grains were dynamically recrystallized to quartz aggregates within the margin of the granitic plutons (Fig. 4). The data on quartz grain sizes in Fig. 7 show that the mean grain size abruptly becomes uniform in SE of QZ near the margin of the granitic plutons. The grain size distributions also shift to those of finer grains on log-normal plots (Fig. 6).

It is well known from theoretical and experimental studies that the recrystallized grain size is predominantly a consequence of the stress conditions during deformation (e.g. Twiss 1977, Mercier *et al.* 1977, Guillope & Poirier 1979, Ranalli 1984, Derby 1990). Recent work in progress suggests that the Kashio shear zone appears to develop a steady-state grain size which is defined by *mean* grain sizes rather than individual grains within dynamically recrystallized quartz aggregates: each grain in the quartz aggregates would be either dynamically recrystallized (i.e. grain size reduction) or recovered (i.e. grain growth) on log-normal distribution, while mean grain sizes reach a steady-state size (Michibayashi in preparation). Thus as the strain increases, the mean grain size decreases until it reaches a steady-state size (cf. Shimamoto 1989). In this way, the relatively uniform mean grain sizes in Fig. 7 appear to reach the lower bound of mean grain sizes in dynamically recrystallized quartz aggregates within this shear zone (Michibayashi in preparation), that is a steady-state grain size. However, this does not mean that the abrupt grain size reduction across the boundary, QZ, generally occurs only as a result of this process. This is discussed below.

Plastic–brittle transition for feldspar during shear zone development

Recrystallized plagioclase grains occur parallel to the mylonitic foliation (S_m; Fig. 5c), indicating that the mylonitic deformation possibly occurred at medium temperature conditions (e.g. Simpson 1985, Gapais 1989). The temperature of the onset of feldspar recrystallization was experimentally estimated as above 450°C (e.g. Tullis & Yund 1985), and these fabrics have predominantly been documented from deformed rocks within or higher than upper-greenschist facies (i.e. Simpson 1985, Jensen 1985, Gapais 1989, Gate & Glover 1989). K-feldspar grains are commonly replaced by myrmekite along zones lying subperpendicular to S_m within the mylonitic granites (Fig. 5f). According to Simpson & Wintsch (1989), deformation-controlled myrmekitic replacement occurs at amphibolite facies conditions, suggesting that the Kashio shear zone was initiated at relatively higher temperatures (i.e. ≥450°C). Since these granitic rocks were not metamorphosed, this shear zone could have developed during cooling of the Ryoke granitic plutons (e.g. Hayama & Yamada 1980) or even during emplacement (cf. Paterson *et al.* 1989).

Both K-feldspar and plagioclase porphyroclasts are overprinted by brittle deformation microstructures, with quartz infilling the fractures, especially near the pluton margins (Figs. 5b & e and 8). The quartz infill has locally been recrystallized, suggesting that both feldspar types passed through their plastic–brittle transition during the later stages of deformation while quartz continued to deform plastically. This indicates that the deformation occurred at lower temperatures within the greenschist facies (e.g. Gapais 1989). Consequently, these microstructures reflect cooling of the granitic rocks from the ductile to semi-ductile (ductile–brittle) regime (e.g. Sibson 1977, 1983, Shimamoto 1989) during shear zone development. Displacement of fractured segments in conjunction with asymmetric geometries around feldspar porphyroclasts within the mylonites indicate that the direction of the shear movement did not change during cooling.

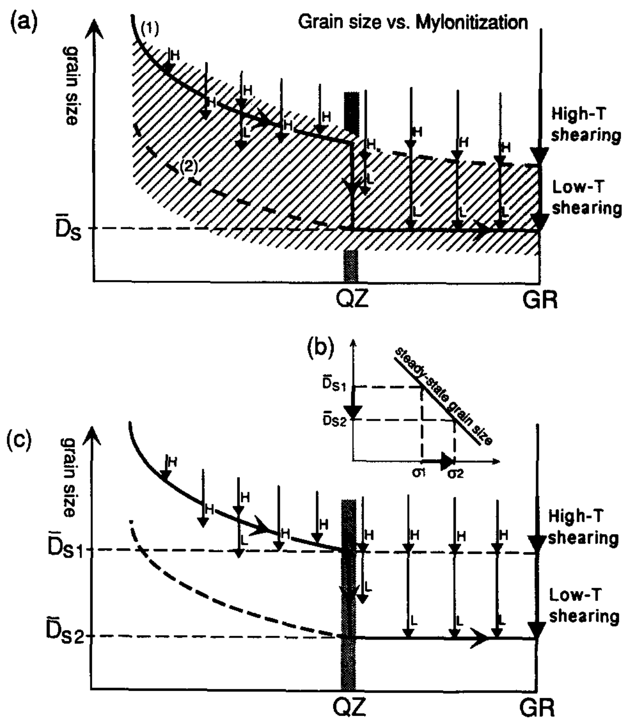


Fig. 9. Evolution of quartz aggregate grain sizes during mylonitization. GR, the margin of the Ryoke granitic plutons; QZ, the boundary where an abrupt grain size reduction occurs. Small arrows in (a) and (c) indicate a history of mean grain sizes within individual quartz aggregates; arrows labelled H, grain size reduction during high-T shearing; arrows labelled L, grain size reduction during low-T shearing. Shaded area shows possible grain size distribution of quartz. (a) Path (1); solid line—an abrupt change in mean grain size reduction towards a steady-state grain size ($\bar{D}_S$) across QZ as a result of a strain localization during the progressive retrogression. Path (2); from a broken line to a solid line—a gradual reduction in mean grain size towards $\bar{D}_S$. (b) Mean grain size ($\bar{D}$) as a function of deviatoric stress (σ). A thick line indicates idealized steady-state grain size correlated with stress. $\bar{D}_{S1}$, a steady-state grain size under high-T plastic deformation; $\bar{D}_{S2}$, a 'revised' steady-state grain size correlated with a higher deviatoric stress (σ_2) under low-T plastic–brittle deformation. (c) Solid line, an abrupt change in mean grain size reduction resulting from a shift of steady-state grain size from $\bar{D}_{S1}$ to $\bar{D}_{S2}$ during the progressive retrogression. See text for discussion.

The effect of progressive retrogression

Brittle deformation of feldspar occurs predominantly within the zone, where the mean grain sizes in quartz aggregates appear to reach a steady-state grain size as a result of dynamic recrystallization (Figs. 7 and 8). Displacement and/or pull-apart of fractured feldspar porphyroclasts in the quartz matrix within this zone indicate that strain within the rocks increased further under the low-temperature conditions. Therefore, the zone producing the discontinuity in mean grain sizes reflects a localized zone that underwent shearing at low-T (e.g. greenschist facies) conditions, after the earlier high-T (e.g. amphibolite facies) conditions (Fig. 8). Consequently, the Kashio shear zone can be interpreted to develop under the retrogressive conditions so that the shear zone narrowed towards the pluton margins, suggesting that strain localization occurred during cooling of the granitic rocks (cf. Hara *et al.* 1980).

The mean grain size reduction in quartz aggregate toward the Median Tectonic Line has been used to indicate higher strain (e.g. Hara *et al.* 1977, 1980, Takagi 1986, 1989). However, if the grain size reduction dominantly resulted from dynamic recrystallization, the reduction process would be weakened and the mean grain size become stable when they reached a steady-state grain size ($\bar{D}_S$) in association with a certain amount of strain (Michibayashi in preparation). As a consequence, the mean grain sizes in quartz aggregates would become independent of strain. Therefore, although quartz grain sizes may be regarded as an evidence for plastic deformation, it is unlikely that they are strain indicators (cf. Hara *et al.* 1980, Takagi 1989). Moreover, alternative explanations are in general possible in conjunction with deformation conditions.

If the P–T conditions were relatively stable during mylonitization, the mean grain size would decrease gradually and become stable towards the centre of the shear zone (path 2 in Fig. 9a). If the P–T conditions changed (e.g. the temperature decreases to greenschist facies during a progressive deformation), earlier high-T shearing could develop in wider zones and form initially gradual grain size reduction of quartz across the shear zone (e.g. arrows labelled H in Fig. 9a). However, during later low-T shearing, the shear zone would narrow as a consequence of strain localization, and only a narrower zone towards the shear zone centre would be further deformed and result in development of a steady-state grain size ($\bar{D}_S$ and arrows labelled L in Fig. 9a). This would produce a discontinuity in the mean grain size without a tectonic boundary being present (i.e. path 1 across QZ in Fig. 9a; cf. Hara *et al.* 1980, Takagi 1986).

Alternatively, since rocks at lower temperatures would be more competent than at higher temperatures, further deformation, which is mainly accommodated by quartz plastic flow, may require higher deviatoric stress conditions. This could lead further dynamic recrystallization in quartz aggregates to a 'revised' steady-state grain size ($\bar{D}_{S2}$ in Figs. 9b & c) that shifted to a finer size in equilibrium with the higher stress conditions (Fig. 9b), even if mean grain sizes in quartz aggregates had already reached to an early steady-state grain size ($\bar{D}_{S1}$ and arrows labelled H in Fig. 9c). Then, only limited zones, that resulted from a strain localization, would progress to further grain size reduction towards the 'revised' $\bar{D}_{S2}$ during the progressive retrogression (e.g. arrows labelled L in Fig. 9c). This enables an abrupt change in mean grain size across the shear zone (i.e. solid line across QZ in Fig. 9c). However, it should be noted that the stress may not be necessarily increased during the progressive retrogression.

The mechanism in quartz recrystallization for further grain size reduction may subsequently change during the progressive retrogression. For instance, Guillope & Poirier (1979) demonstrated that the relationship between steady-state grain size and stress is different for 'rotation' and 'migration' recrystallization. As a change in mechanism commonly depends on temperature and/or strain rate (e.g. Masuda & Fujimura 1981, Hirth & Tullis 1992), it may affect the degree of discontinuity in grain size reduction.

During deformation under the presence of a certain amount of a fluid phase, these rocks could be also affected by pressure solution or shear-induced dissolution and solution transfer (e.g. Cox & Etheridge 1983, 1989, Bell & Cuff 1989, O'Hara 1990). Although this effect is negligible within the rocks in this study, it may result in further grain size reduction after a dynamically recrystallized steady-state grain size was established.

Origin of the Kashio shear zone

Dallmeyer & Takasu (1992) recently reported that mineral ages preserved within the Ryoke granites could reflect two stages of relatively rapid cooling (Fig. 10a); 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). They also suggested that the mylonitization developed at 62–63 Ma (Middle Paleocene), under temperature conditions at which biotite recrystallized (i.e. 300 ± 25°C). According to the isochronological data of Dallmeyer & Takasu (1992), our model for the development of the Kashio

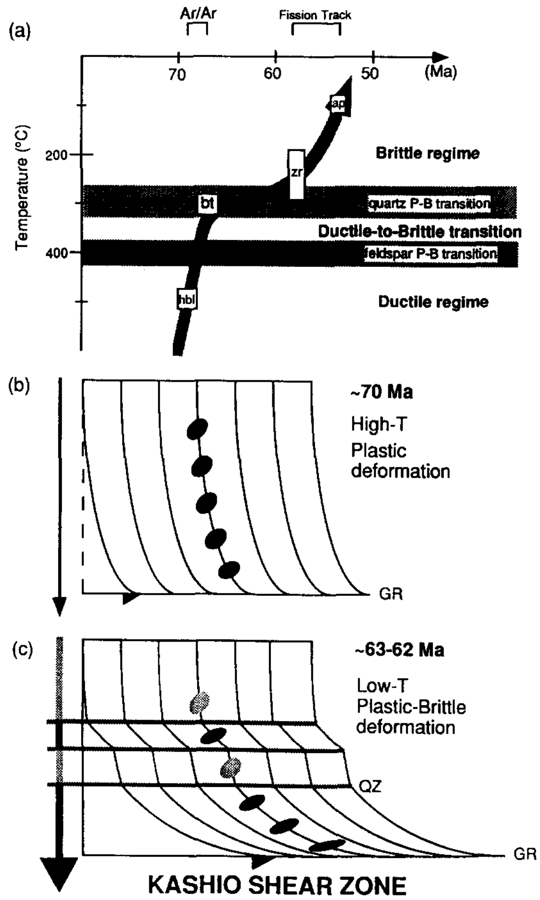


Fig. 10. (a) Time–temperature evolution for the Ryoke granitic pluton, Chubu district, Japan (after Dallmeyer & Takasu 1991). $^{40}Ar/^{39}Ar$ hornblende (hbl) and biotite (bt) ages from Dallmeyer & Takasu (1992), and fission track zircon (zr) and apatite (ap) ages from Tagami *et al.* (1988). The temperatures of the plastic–brittle transition for feldspar and quartz from Tullis & Yund (1977, 1985) are shown with uncertainty limits (shaded areas). (b)&(c) Idealized strain diagrams to show relationship between high-T and low-T shear zone development within the margin of the Ryoke granitic pluton in relation to development of the Kashio shear zone. Approximate ages after Dallmeyer & Takasu (1992). (b) Before the granitic rocks cooled down below 450°C, shear deformation affected the granites so that they developed gneissosity with graded into high-T mylonitic fabrics near their margins. (c) During or after cooling to 300°C, the shear deformation developed progressively so that mylonitic fabrics within the granites were developed within a localized zone towards the shear centre. The Kashio shear zone was established by this event. The boundary of maximum quartz recrystallization (QZ) occurred as a consequence of this retrogressive development of the shear zone.

shear zone can be related to the regional geologic evolution as follows.

After or during intrusion of the Ryoke granitic plutons, the plutons were sheared and developed into gneissoid granites before 70 Ma (Fig. 10b). At this stage, deformation within the granites was weak, and therefore, although quartz grains were recrystallized (e.g. Figs. 4a–c), feldspars were affected only along their grain boundaries (e.g. Figs. 7a & d). During the period 70–66 Ma, the granites cooled to 300°C (Fig. 10a), and the zone affected by the shear movement become narrower because of the strain localization associated with these retrogressive conditions (see above). After this rapid cooling event (at approximately 62–63 Ma), the shear deformation continued to develop under progressively more retrogressive P–T conditions (Fig. 10c). Consequently, the quartz grains were sufficiently recrystallized to reach a steady-state grain size accompanied by the brittle deformation of feldspars within a narrow zone (cf. Figs. 8 and 9). By this stage, this narrow zone had become established as a mylonite zone within the Kashio shear zone (Fig. 10c).

Although the Kashio shear zone is mainly regarded as this narrow zone (e.g. Hayama & Yamada 1980, Takagi 1986, Dallmeyer & Takasu 1992), we suggest that when the Ryoke granites were crystallized, the initial shear deformation occurred but could be weak enough to preserve intracrystalline argon systems within hornblende (cf. Dallmeyer & Takasu 1992). Therefore, the emplacement of these granites may be correlated with this deformation (cf. Paterson *et al.* 1989) or directly associated with the development of the Median Tectonic Line (cf. Morand 1992).

CONCLUSION

The Kashio shear zone preserves two stages of deformation that differ through a drop in temperature. One resulted from the earlier but weaker plastic deformation that formed gneissosity within the granites, and the other resulted from the later and stronger plastic–brittle deformation that occurred dominantly within a narrow zone along the margin of the granites (Fig. 10c). During the latter deformation, the mean grain size within dynamically recrystallized quartz aggregate reached a steady-state size, at around 35 μm on a log-normal distribution.

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