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4 **Development of a shear band cleavage as a result of strain partitioning**

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Abstract

Microstructural analyses of shear band cleavages in a centimeter-scale shear zone within a metasomatic biotite band in the Teshima granite, Ryoke metamorphic belt, southwest Japan, show that strain partitioning occurred between quartz and biotite-feldspar domains within the shear zone. Pre-tectonic hydrothermal alteration within the granite caused biotite replacement of both plagioclase and K-feldspar, resulting in the development of biotite-feldspar domains where K-feldspar mantles dominantly biotite-plagioclase aggregates. Subsequently, the altered granite was plastically deformed in simple shear, so that intra-layer shear band cleavages were passively developed within the biotite-feldspar domains, whereas intense dynamic recrystallization occurred in the quartz domains. The rotation and orientation of the intra-layer shear band cleavages can be explained by a finite strain ellipse model, which shows that strain in the biotite-feldspar domain requires only 10 to 20 % of the bulk simple shear strain for the development of such cleavages, so that most of strain could be accommodated by deformation in the quartz domain. Consequently, the model suggests that the development of the shear zone resulted in strain partitioning between the quartz and the biotite-feldspar domains due to compositional variations via hydrothermal alteration within the granite.

Key words: Shear band cleavage, shear zone, strain partitioning, alteration, granite, strain analysis, Ryoke metamorphic belt

33 **1. Introduction**

34

35 Within deformed rocks, a mica-preferred orientation or compositional layering
 36 may be transected at a small angle by sets of subparallel minor shear zones, known as
 37 shear band cleavages (Passchier and Trouw, 2005). Shear band cleavages are commonly
 38 slightly oblique to the direction of shear, and have been variously referred to as
 39 C'-surfaces (e.g., Berthé et al., 1979; Blenkinsop and Treloar, 1995; Pray et al., 1997),
 40 shear bands (White et al., 1980; Gapais and White, 1982), extensional crenulation
 41 cleavage (Platt and Vissers, 1980) and normal slip crenulation (Dennis and Secor,
 42 1987). Shear band cleavages are extensively used as shear sense indicators in shear
 43 zones (e.g., Berthé et al., 1979; Lister and Snoke, 1984), although their development is
 44 not fully understood (Passchier and Trouw, 2005). This is because it is difficult to obtain
 45 reliable data from natural shear zones on factors such as deformation history, initial
 46 orientation of shear bands, bulk and local finite strain, and bulk and local volume
 47 change (Passchier, 1991).

48 In this paper, we conducted a simple geometric analysis of shear band
 49 cleavages along a strain gradient from the margin to the centre of a centimeter-scale
 50 shear zone. As a result, we demonstrate that a finite strain ellipse model proposed by
 51 Platt (1984) could explain the development of shear band cleavages in this small shear
 52 zone.

53

54 **2. Regional geology and sample description**

55

56 The sample analysed in this study was collected from Teshima island in the
 57 Shiwaku Island Group, Japan, within the Ryoke HT/LP metamorphic belt (Fig. 1; e.g.,
 58 Hara et al., 1973; Arita, 1988). Gneissic coarse-grained hornblende-biotite granite
 59 occurs in the south of the island, and weakly gneissic medium-grained biotite granite
 60 and hornfels occur in the north of the island (Fig. 1; Arita, 1988).

61 The introduction of iron-bearing fluid phases resulted in hydrofracturing in the
 62 northwestern part of the biotite granite and the formation of thin metasomatic biotite
 63 bands (thickness: 5-10 cm), some of which contain quartz veins in the middle of the

bands (thickness: 1-4cm); the biotite bands are subvertical and strike approximately 20° (Michibayashi et al., 1999). The bands locally occur as anastomosing networks. The bands resulted from biotite replacement of mainly plagioclase and K-feldspar grains with the addition of iron-bearing fluids (Fig. 2). The mineral replacements weakened this part of the granite, and small-scale sinistral shear zones developed within those parts of the granite that contain quartz veins and biotite bands (Michibayashi et al., 1999).

The analysed sample was taken from a metasomatic biotite band, and contains one side of a shear zone, where a shear plane of the shear zone centre is subparallel to the strike and dip of the biotite band (Fig. 2). The protolith is a medium-grained biotite granite, which consists of quartz, plagioclase, K-feldspar and biotite, with minor zircon and muscovite. EPMA chemical analysis revealed that plagioclase grains are An₅₋₁₆, K-feldspar grains are Or₉₂₋₉₆, and biotite grains are iron-rich, with Mg/(Fe+Mg)=0.05-0.07 (Togami et al., 2000).

In the sampled rock, biotite layers define a foliation within the biotite band, which shows some degree of obliquity with respect to the centre of the shear zone (Fig. 2). This obliquity provides a continuous gradient from high angle at relatively unstrained to low angle at highly deformed over a distance of several centimeters. Here, we define a distance (d) normal to the shear plane of the shear zone centre ($d=0$).

3. Microstructures

Element mapping by X ray fluorescence studied by Michibayashi et al. (1999) showed that quartz modal composition increases toward the centre of the shear zone. Michibayashi et al. (1999) defined the three domains according to a zonation in the metasomatised band: the quartz domain, biotite domain and K-feldspar domain. In this paper, although we study the microstructures that occur mostly in the quartz domain and partly in the biotite domain of Michibayashi et al. (1999), it is rather convenient to re-divide microstructures within these two domains into two dominant domains: quartz domains and biotite-feldspar domains as follows.

95 3.1. Quartz domains

96

97 The quartz domains contain quartz grains with feldspar inclusions and become
 98 more dominant toward the centre of the shear zone. Modal composition analysis showed
 99 that modal composition of the quartz domain increases from the biotite band to the
 100 centre of the shear zone by up to 60 % (Michibayashi et al., 1999).

101 Figure 3A shows quartz grains within the relatively undeformed granite at $d=15$
 102 cm. Grains have weak serrated boundaries with stable triple points, indicating minimal
 103 deformation. At the margin of the shear zone ($d=4\text{cm}$), quartz grains have developed a
 104 slightly elongate shape without formation of a foliation (Fig. 3B), indicating that bulk
 105 strain is low. At $d=2.5$ cm, quartz grains are weakly elongate subparallel to S-foliation
 106 (Fig. 3C) and in part recrystallized, with intensely serrated grain boundaries and strong
 107 undulose extinction. At $d=1.5$ cm, deformation in quartz is further intensified (Fig. 3D).
 108 Although igneous quartz grains are still visible, intracrystalline deformation has resulted
 109 in strong undulose extinctions and serrated grain boundaries. At $d=1$ cm, quartz grains
 110 are intensely elongated parallel to S-foliation, and dynamic recrystallization has resulted
 111 in a reduction in grain size (Fig. 3E). The intensity of dynamic recrystallization increases
 112 toward the shear zone centre (Fig. 3F). The grain size of quartz is reduced from ca. 0.5
 113 mm in the undeformed granite (Fig. 3A) to ca. 50 μm within the shear zone (Fig. 3F).
 114 Fine K-feldspar inclusions within the quartz domains are also elongated parallel to
 115 S-foliation.

116 Quartz crystal-preferred orientations (CPOs) were measured from highly
 117 polished thin section using a JEOL 6300 SEM equipped with electron back-scattered
 118 diffraction (EBSD) at Shizuoka University, Japan. Quartz CPOs show triclinic
 119 symmetries with the girdle of c-axes subparallel to the Y-axis toward to the centre of
 120 the shear zone, although quartz CPOs at $d=2.5\text{-}3.5\text{cm}$ have a triclinic symmetry slightly
 121 oblique to XZ plane (Fig. 4). These patterns show that prism $\langle a \rangle$ slip was dominant in
 122 this shear zone (e.g., Passchier and Trouw, 2005).

123

124 3.2. Biotite-feldspar domains

125

126 The biotite-feldspar domains consist mainly of secondary fine-grained biotite
 127 and plagioclase aggregates (Fig. 5). Michibayashi et al. (1999) showed that primary
 128 plagioclase grains occur as a matrix to the fine-grained biotite aggregates and that the
 129 biotite-feldspar domains are commonly mantled by K-feldspar (Fig. 6; see also fig 3 of
 130 Michibayashi et al., 1999). The amount of fine-grained biotite grains in plagioclase tends
 131 to increase towards the centre of the shear zone (Michibayashi et al., 1999). The shear
 132 band cleavages studied in this paper occur dominantly in the biotite-feldspar domains.

133 In the relatively undeformed granite at $d=15$ cm, biotite occurs as randomly
 134 oriented euhedral primary grains (Fig. 5A). Secondary fine-grained biotite aggregates
 135 first occur within coarse plagioclase grains at $d=4$ cm (Fig. 5B). Deformation is weak
 136 and the secondary biotite grains have no preferred orientation. The biotite-feldspar
 137 domains become elongated at $d=2.5$ cm and define an S-foliation at the margin of the
 138 shear zone (solid line in Fig. 5C). The angle between the S-foliation and the shear plane
 139 is as high as 45° . However, the secondary biotite grains within plagioclase grains are
 140 randomly oriented (Fig. 5C and 6A).

141 The characters of the biotite-feldspar domains change gradually toward the
 142 shear zone centre. At $d=2$ cm, the domains become elongate parallel to the S-foliation,
 143 and the secondary biotite grains are sheared, resulting in the initiation of intra-layer
 144 shear band cleavage subparallel to the shear plane (Fig. 5D). The biotite-feldspar at $d=1$
 145 cm where the secondary biotite have developed are further elongated parallel to the
 146 S-foliation (Fig. 5E and 6B). The secondary biotite grains are intensely deformed, and
 147 many shear band cleavages have developed.

148 Within the centre of the shear zone, biotite-feldspar domains are strongly
 149 elongated parallel to the S-foliation (Fig. 5F) and intra-layer shear band cleavages are
 150 pervasively developed. Although the S-foliation is oriented subparallel to the shear
 151 plane, the intra-layer shear band cleavages occur at about 10° to 20° to both S-foliation
 152 and the shear plane.

153 The shear band cleavages described above are of the intra-layer type, as they
 154 occur only within the biotite-feldspar domains. Inter-layer type shear band cleavages
 155 also occur in the vicinity of the shear zone centre (Figs 2B and 7). Displacements along
 156 the inter-layer shear band cleavages are relatively large, and cut across the

157 biotite-feldspar domains, the quartz domains (Figs 2B and 7) and the intra-layer shear
158 band cleavages.

159 It is important to note that there is no evidence of overgrowth of any minerals
160 on the shear band cleavages (Figs 5 and 6). This suggests that the development of such
161 planar fabrics occurred after the metasomatic reactions in the biotite band (e.g.,
162 Michibayashi et al., 1999).

163

164 **4. Geometric analysis**

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166 *4.1. Methods*

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168 We performed a microstructural analysis to investigate variations in the
169 geometry of the shear band cleavages across the shear zone. Four parameters were
170 measured with the aid of an optical microscope: (i) spacing of adjacent shear band
171 cleavages, (ii) the angle between the S-foliation and the shear plane (ϕ), (iii) the angle
172 between the shear band cleavage and the shear plane (ψ), and (iv) the angle between
173 the S-foliation and the shear band cleavage (η ; Fig. 8A) which equals $\phi + \psi$.

174

175 *4.2. Results*

176

177 Results are shown in Fig. 8B-E. Open diamonds indicate the biotite-feldspar
178 domains where a S-foliation occurs without shear band cleavage (e.g., Fig. 5C), and in
179 this case only one parameter (ϕ) has been measured (Fig. 8C). Solid circles represent the
180 data for the intra-layer shear band cleavages, whereas open triangles show those for the
181 inter-layer shear band cleavages.

182 Figure 8B shows that the spacing of the intra-layer shear bands varies from 0.5
183 to 2 mm away from the shear zone centre, whereas it tends to be in a small range
184 between 0.2 and 0.5 mm near the shear zone centre. Figure 8C shows the trend of
185 S-foliation with respect to the shear plane (ϕ) across the shear zone. Several points of
186 biotite-feldspar domains record ϕ angles of $> 45^\circ$. There is no shear band cleavage
187 within such high-angle biotite-feldspar domains (Fig. 8C). Shear band cleavage occurs

188 where the angle of the S-foliation to the shear plane (ϕ) is less than 45° (Fig. 8C).

189 The angle between the intra-layer shear band cleavage and the shear plane (ψ)
 190 shows a gradual change from sub-parallel to the shear plane to negatively oblique
 191 orientation as the distance to the shear zone centre decreases (Fig. 8D). The inter-layer
 192 shear band cleavages appear for a distance $d < 10$ mm (Fig. 8D). Their angles are
 193 narrower than those of the inter-layer cleavages and show no tendency with respect to
 194 the distance from the shear zone centre. The angle between S-foliation and the shear
 195 band cleavages (η) has a scattered distribution (Fig. 8E).

196 In order to examine the relationship between three parameters (ϕ , ψ , η), we
 197 made a variation diagram between ϕ and ψ (Fig. 9), where each line shows a stable
 198 value of the angle (η) as $\psi = \phi - \eta$ that is defined in Fig. 8A. It appears that the angles
 199 between the S-foliation and the shear band cleavages became somehow narrower as ϕ
 200 being smaller. Notice that the inter-layer shear band cleavages tend to occur where the
 201 intra-layer shear band cleavages are at higher angles to the shear plane.

202

203 **5. Interpretation and discussion**

204

205 *5.1. The evolution of planar fabrics with respect to simple shear strain*

206

207 From the measured spatial variations in microstructural development described
 208 above, we have sought to model temporal changes by assuming that the intra-layer
 209 shear band cleavages close to the centre of the shear zone preserve more progressively
 210 developed types than those at away from the centre of the shear zone. This small-scale
 211 shear zone occurs within largely undeformed granite. Although this shear zone occurs in
 212 a metasomatic biotite band, we consider that volume change during deformation was
 213 minimal, as there is no evidence of overgrowth or dissolution of minerals on the shear
 214 band cleavages. Hara et al. (1973) examined quartz c-axis orientations in this area and
 215 also concluded that the shear zones formed under conditions of simple shear strain.
 216 Quartz CPOs in Fig. 4 could also result from simple shearing in quartz. Although quartz
 217 CPOs at $d = 2.5\text{--}3.5\text{ cm}$ are slightly oblique, its triclinic symmetry is still maintained.
 218 Therefore, a simple shear strain model is a suitable first order estimation of the bulk

219 kinematic framework. As a consequence, we interpret the development of the shear
220 band cleavages in terms of bulk simple shear.

221 In general, there are two alternative interpretations of ϕ : either (i) as the
222 direction of the instantaneous stretching axis (i.e. $\tan 2\phi = 2\gamma$; e.g., Ramsay and
223 Graham, 1970), or (ii) the direction of a material line that orients an initial angle (i.e.
224 $\cot\phi = \cot\phi_0 + \gamma$; e.g., Platt, 1984). In the latter case, estimated simple shear strain
225 varies in dependent on an initial direction of the line (ϕ_0). We estimated the amount of
226 simple shear strain for both cases in Fig. 10, where the initial angle of the material line
227 was assumed to be $\phi_0 = 60^\circ$ after Fig. 8C as an example.

228 Figure 10 shows the evolution of two parameters with respect to progressive
229 simple shear strain. Figure 10A shows that the intra-layer shear band cleavages have
230 been progressively rotated from 10° to -20° as strain increased to $\gamma=2$ (see also Fig. 8D).
231 The direction of the shear band cleavages appears to become relatively stable at an
232 angle oblique to the shear plane regardless of simple shear strain (Fig. 10A). The angle
233 between the S-foliation and the intra-layer shear band cleavage decreases gradually
234 from 50° to 20° as strain reaches $\gamma=9$ (Fig. 10B; cf. Fig. 8E).

235 Figure 11 shows our interpretation of the development of the shear band
236 cleavage based on the microstructural observations and the geometric analyses. An
237 S-foliation developed first (Stage 0). As strain increased, the S-foliation was rotated and
238 stretched, resulting in the formation of intra-layer shear band cleavage (Stage 1). In
239 contrast to the S-foliation that occurred at high angle to the shear plane (i.e. ca. $\phi=45^\circ$;
240 Fig. 8C), the intra-layer shear band cleavage formed subparallel to the shear plane (i.e.
241 ca. $\psi = 0$; Figs. 8D and 10A), where the angle between the S-foliation and the
242 intra-layer cleavage was as high as 50° (Figs. 8E and 10B). With increasing strain, the
243 intra-layer shear band cleavages developed into discrete cleavages separated by
244 microlithons (Stage 2a). As shown in Fig. 9, the angle η between the S-foliation and the
245 shear band cleavage appears to be at around 40° at lower strain, whereas the S-foliation
246 was rotated towards the shear plane. As strain increased further, the S-foliation rotated
247 close to the shear plane, and the angle between the S-foliation and the shear band
248 cleavage became smaller (Stage 2b; Figs. 8E and 10B). Finally, the inter-layer shear

band cleavages cut across the intra-layer shear band cleavages that contain mainly Stage 2b microstructures (Stage 3).

5.2 A finite strain ellipse model for the intra-layer shear band cleavages

Numerous models of the origin and evolution of planar fabrics in shear zones have been proposed (e.g., Ramsay, 1967; 1980; Berthé et al., 1979; Platt and Vissers, 1980; Platt, 1984; Lister and Snoke, 1984; Bobyarchick, 1986; Dennis and Secor, 1987; 1990; Passchier, 1991; Blenkinsop and Treloar, 1995; Pray et al., 1997). The different models predict different relationships between the bulk strain ellipsoid and the foliation (Blenkinsop and Treloar, 1995). For example, several studies describe the formation of S-fabrics parallel to the long axis of the finite strain ellipse in simple shear (e.g., Ramsay, 1967; 1980; Berthé et al., 1979; Lister and Snoke, 1984; Blenkinsop and Treloar, 1995). However, Platt (1984) suggested that slip could occur parallel to S-fabrics due to strain partitioning in overall simple shear (cf. Dennis and Secor, 1987; 1990).

With respect to shear band cleavages, Bobyarchick (1986) suggested that the inclined eigenvector may represent the orientation of shear bands in natural shear zones. Pray et al. (1997) showed that if the shear-surface was parallel to such an inclined eigenvector in a convergent shear zone, the S- and C-surfaces developed stable orientations and ceased to rotate. However, Simpson and De Paor (1993) argued that the eigenvector direction is an unstable direction, and once a plane is deflected slightly from this orientation, it will continue to rotate away from the eigenvector. Simpson and De Paor (1993) favored a model in which shear bands propagate along surfaces close to the direction of maximum shear strain rate (see also Platt and Vissers, 1980; Ramsay and Lisle, 2000). In contrast, Blenkinsop and Treloar (1995) noted a geometrical similarity between shear surfaces in ‘brittle shear zones’ and S-C mylonites, and proposed that shear band cleavages form in the orientation of a Coulomb failure surface at an angle of less than 45° to the maximum principal stress.

Our data revealed that the intra-layer shear band cleavages could be progressively rotated with increasing strain (Fig. 10). Therefore, it appears that any

280 fabric attracter models may not explain the rotation of the intra-layer shear bands, as
 281 the eigenvector direction parallel to the shear plane is thought to be the convergent
 282 direction for both positive and negative angles of foliation to the shear plane. On the
 283 contrary, a model with respect to the finite strain ellipse may be able to describe their
 284 rotational behavior, since it is well known that the rotational component of the finite
 285 strain ellipse exceeds the stretching component at lower strains, and subsequently its
 286 stretching component becomes dominant (e.g., Ramsay and Huber, 1983).

287 Another important feature of the data is that the intra-layer shear band
 288 cleavages became more discrete, where the spacing of the cleavage was nearly stable
 289 (Fig. 8B). This means that shearing along the cleavages became dominant with
 290 increasing strain. Ramsay and Lisle (2000) suggested that shear band cleavages develop
 291 as a result of shear instability early during deformation, but once formed, they guide
 292 successive shear instabilities into the pre-existing shear band. However, although
 293 Ramsay and Lisle (2000) proposed that the shear bands will be oriented close, but not
 294 parallel to the position of maximum finite shear strain at any stage of deformation, our
 295 model shown below works in terms of passive rotation of previously formed material
 296 lines. Therefore, the orientations of the cleavages are not related to the position of
 297 maximum finite shear strain at any stage.

298 Ishii (1992) investigated theoretical deformation paths in layered rock masses
 299 and showed that layers with viscosity contrast deform by different amounts of
 300 non-coaxiality; layers with low viscosity tend to deform by simple shear, and layers with
 301 high viscosity tend to deform coaxially (see also Jiang, 1994; Ishii, 1996). In our study,
 302 the quartz domains may be good candidates for layers with low viscosity, where simple
 303 shear deformation is dominant. In contrast, the biotite-feldspar domains have relatively
 304 high viscosity due to mantled K-feldspar (Fig. 6), and deformed coaxially. In this way, a
 305 model originally proposed by Platt (1984) may demonstrate the rotational behavior of
 306 the intra-layer shear band cleavages as follows.

307 We consider that a shear band cleavage rotates as a passive marker with
 308 respect to coaxial stretching (E^s), which is:

$$309 \quad \tan \eta = \tan \eta_0 \left(\frac{1}{E^s} \right)^2, \quad (1)$$

where E^S is parallel to the S-foliation (Platt, 1984) and $\eta = \phi - \psi$ as defined in Fig. 8A. E^S can be defined as a function of the maximum strain (E_I). In simple shear,

$$\left(\frac{1}{E^S}\right)^2 = \left(\frac{1}{E_1}\right)^2 \cos^2 \beta + \left(\frac{1}{E_2}\right)^2 \sin^2 \beta \quad (2)$$

$$(E_1)^2 = \frac{1}{2} \left[\gamma^2 + 2 + \gamma \sqrt{\gamma^2 + 4} \right], \quad (3)$$

where $E_2 = 1/E_1$ and $\beta = \delta - \phi$ (Ramsay, 1967; Platt, 1984). δ is the angle between E_I and the shear plane: i.e.

$$\tan 2\delta = 2/\gamma. \quad (4)$$

With respect to the relationship between simple shear strain (γ) and the S-foliation (ϕ), there are two expressions depending on how we deal with the direction of the S-foliation. If we assume that the S-foliation rotates as a passive marker in simple shear, then

$$\cot \phi = \cot \phi_0 + \gamma. \quad (5)$$

Alternatively, if we assume that the S-foliation is parallel to the maximum stretching axis of a strain ellipsoid, then

$$\phi = \delta. \quad (6)$$

Here, we modified equation (3) further to:

$$(E_1)^2 = \frac{1}{2} \left[\Gamma^2 + 2 + \Gamma \sqrt{\Gamma^2 + 4} \right], \quad (7)$$

where

$$\Gamma = \Delta \gamma \quad (0 \leq \Delta \leq 1). \quad (8)$$

Δ represents the proportion of the bulk simple shear strain (γ), which defines an effective simple shear strain (Γ) for coaxial stretching. In this model, the rotation rate of the strain ellipse is the same as that of the simple shear strain ellipse, while the stretching rate varies from the simple shear strain ellipse according to the value of Δ . For instance, if $\Delta = 1$, then $\Gamma = \gamma$, which follows the path of the simple shear strain ellipse. If $\Delta = 0$ and $\Gamma = 0$, such that the S-foliation accommodates no strain, then rotation of the shear band cleavages occurs at the same rate as that of the S-foliation.

Figure 12A shows a series of rotation paths for ψ with respect to Δ and γ .

When $\Delta = 1$, the stretching component is dominant and only minor rotation occurs at low strain. ψ is closer to 0 as strain increases (i.e. shear band cleavages become closer to the shear plane). In contrast, as Δ decreases, the rotation component is dominant over the stretching component, such that ψ decreases rapidly at lower strain and becomes stable. Figure 12B shows evolution paths for η with respect to Δ and γ . In the case of simple shear ($\Delta=1$), η decreases rapidly at low strains ($\gamma < 2$ in Fig. 12B) because of the effect of intense stretching. However, as Δ approaches 0, the rate of decrease in η is reduced.

Comparing the model results with our data, the paths that represent $0.1 \leq \Delta \leq 0.2$ appear to agree with the data. This suggests that internal strain within the biotite-feldspar domains may represent as little as 10 to 20 % of the bulk simple shear strain, suggesting that the kinematic development of intralayer shear bands may be a response to very local kinematic conditions and not the bulk shear. Such local strains within the biotite-feldspar domains can be explained by their microstructural features; they are mantled by K-feldspar (Figs. 5 and 6). Thereby, the biotite-feldspar domains could not be intensely deformed during shearing, even though biotite grains occur in the domains. The majority of strain may be therefore accommodated with deformation in the quartz domains. It suggests that the development of the shear zone resulted in strain partitioning between the quartz and the biotite-feldspar domains. The shear zone occurs within the metasomatic biotite band in the granite. The development of the shear zone resulted in strain partitioning between the quartz and the biotite-feldspar domains due to compositional variations that occurred by hydrothermal alteration within the granite.

5.3. Development of the inter-layer shear band cleavages

Inter-layer shear band cleavages cut across both the S-foliation and the intra-layer shear band cleavages, and influenced plastic flow in the quartz domain (Fig. 5: curved quartz domains). This suggests that the inter-layer shear band cleavages occurred late during the development of the shear zone, and are, therefore, comparable with shear band cleavages reported by many researchers. Also, angles between the

inter-layer shear band cleavages and the shear plane are relatively stable at -5° to -10° , suggesting that they underwent little rotation during bulk simple shearing. The orientation of shear band cleavages has previously been suggested as representing either the inclined eigenvector during sub-simple shear flow (e.g., Bobyarchick, 1986; Pray et al., 1997), the direction of the maximum rate of shear strain (e.g., Platt and Vissers, 1980; Simpson and De Paor, 1993) or the orientation of a Coulomb failure surface at an angle of less than 45° to the maximum principal stress (Blenkinsop and Treloar, 1995). The first two models seem to require a stable homogeneous flow. Therefore, it is difficult to apply them for the inter-layer shear band cleavages in this study, as they appear to occur within the region of strain partitioning (see above). There is also no positive evidence to support the third model.

The inter-layer shear band cleavages occur where the orientation of intra-layer shear band cleavages became at a higher angle to the shear plane at higher strains (Fig. 9). This suggests that shearing along the intra-layer shear band cleavages may have ceased as their orientations became unsuitable to accumulate shear strain along them. Therefore, it is likely that the inter-layer shear band cleavages developed in those parts of the shear zone where increasing bulk shear strain prevented efficient strain partitioning between the quartz and the biotite-feldspar domains.

Conclusions

Microstructural analyses of shear band cleavages in a centimeter-scale shear zone within a metasomatic biotite band in the Teshima granite, Ryoke metamorphic belt, southwest Japan, show that strain partitioning occurred between quartz and biotite-feldspar domains within the shear zone. Pre-tectonic hydrothermal alteration within the granite caused biotite replacement of both plagioclase and K-feldspar, resulting in the development of biotite-feldspar domains where K-feldspar mantles dominantly biotite-plagioclase aggregate. Subsequently, the altered granite was plastically deformed in simple shear, so that intra-layer shear band cleavages were passively developed within the biotite-feldspar domains, whereas intense dynamic recrystallization occurred in the quartz domains. The rotation and orientation of the intra-layer shear band cleavages can be explained by a finite strain ellipse model. The

398 model shows that strain in the biotite-feldspar domain requires only 10 to 20 % of the
 399 bulk simple shear strain for the development of such cleavages, whereas most of strain
 400 could be accommodated by deformation in the quartz domains. Consequently, the
 401 model suggests that the development of the shear zone resulted in strain partitioning
 402 between the quartz and the biotite-feldspar domains due to compositional variations that
 403 occurred by hydrothermal alteration within the granite.

404

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475 mylonites in ductile shear zones. *Journal of Structural Geology* 2, 175-187.

476 Figure captions

477

478 Figure 1. Geological map of the Shiwaku Islands, SW Japan. Teshima island consists of
479 Ryoke-type granitic rocks and hornfels (Arita, 1988). The sample studied in this
480 paper was taken from the NW side of this island at the locality 'SZ'.

481

482 Figure 2. (A) A rock slab of a small-scale shear zone studied in this paper. The square
483 underlined by a broken line shows the position of the thin section in B. (B)
484 Photomicrograph of one side of the shear zone within the biotite band.
485 Plane-polarized light. Dark biotite-feldspar domains are gradually elongated and
486 rotated towards the shear plane. The intra-layer shear band cleavages occur within
487 the dark elongated biotite plagioclase layers, whereas the inter-layer shear band
488 cleavages cut across both the biotite-feldspar and quartz layers (arrows for
489 example).

490

491 Figure 3. Sequence of photomicrographs under crossed polars illustrating the changing
492 shape of quartz grains from the margin to the centre of the shear zone. (A) $d=15$
493 cm. (B) $d=4$ cm. (C) $d=2.5$ cm. (D) $d=1.5$ cm. (E) $d=1$ cm. (F) $d=0.2$ cm.

494

495 Figure 4. Pole diagrams showing CPO patterns of quartz within the quartz domain with
496 respect to the centre of the shear zone. Equal area projection, lower hemisphere.
497 Contours are in multiples of uniform distribution (m.u.d.). Foliation is vertical and
498 lineation is horizontal within the plane of the foliation.

499

500 Figure 5. Sequence of photomicrographs under plane-polarized light illustrating the
501 changing character of biotite-feldspar domains from the margin to the centre of the
502 shear zone. (A) Euhedral primary biotite grains within the relatively undeformed
503 protolith granite ($d=15$ cm). (B) Secondary fine-grained biotite aggregates within
504 plagioclase grains ($d=4$ cm). (C) Secondary fine-grained biotite aggregates within
505 plagioclase grains ($d=2.5$ cm). Weak S-foliation can be seen (solid line). (D)
506 Secondary fine-grained biotite aggregates within plagioclase grains ($d=1.5$ cm).

Note the development of weak intra-layer shear band cleavages subparallel to the horizontal shear plane. (E) Secondary fine-grained biotite aggregates within plagioclase grains ($d=1$ cm). Discrete intra-layer shear band cleavages occur. (F) Secondary fine-grained biotite aggregates within plagioclase grains ($d=0.2$ cm). Discrete intra-layer shear band cleavages occur at high angles to the subhorizontal shear plane.

Figure 6. Back-scattered electron images of the intra-layer shear band cleavages. The biotite-plagioclase domains (white and dark gray) are mantled by K-feldspar (light gray). (A) Approximately 2.5 cm from the shear zone centre. (B) 1 cm from the shear zone centre.

Figure 7. Photomicrographs of the inter-layer type shear band cleavages, which cut across the biotite-feldspar domains, quartz domains and the intra-layer shear band cleavages at closer angles to the subhorizontal shear plane. The arrow indicates curvature of the quartz domain along the inter-layer cleavages.

Figure 8. (A) Measured parameters for geometric analysis: three angles and spacing with respect to the S-foliation, the intra-layer shear band cleavage (labelled as shear band) and the shear plane. (B) The spacing data with respect to the distance from the shear zone centre. (C) The angle between the S-foliation and the shear plane with respect to the distance from the shear zone centre. (D) The angle between the shear band cleavages and the shear plane. (E) The angle between the S-foliation and the shear band cleavages. Open diamonds indicate data from the biotite-feldspar domains that do not contain shear band cleavages. Solid circles indicate data from the biotite-feldspar domains that contain the intra-layer shear band cleavages. Open triangles show data from the biotite-feldspar domains that contain the inter-layer shear band cleavages.

Figure 9. A diagram showing the angular relationships among the S-foliation, the intra-layer and the inter-layer shear band cleavages with respect to the shear plane.

Solid circles indicate the data for the intra-layer shear band cleavages, whereas open triangles indicate those for the inter-layer shear band cleavages. Each line between solid circle and open triangle shows a cross-cutting relationship between the intra-layer shear band cleavage and the inter-layer shear band cleavage. Broken lines indicate a constant angle (η) between the S-foliation and the shear band cleavages.

Figure 10. (A) The angles (ψ) between the shear plane and the intra-layer shear band cleavages with respect to simple shear strain. (B) The angles (η) between the S-foliation and the intra-layer shear band cleavages with respect to simple shear strain. Shear strains were calculated from the angle (ϕ) between the S-foliation and the shear plane according to two assumptions: (i) ϕ being the material line of a simple shear strain ellipse and the initial angle of the material line: $\phi_0 = 60^\circ$ (gray triangles) and (ii) ϕ being the long axis of the simple shear strain ellipse (solid circles).

Figure 11. Schematic diagram illustrating the development of intra-layer and inter-layer shear band cleavages. (A) Approximate location for each stage with respect to the shear zone. (B) Stage 0: initiation of S-foliation. Stage 1: the intra-layer shear band cleavages were initiated subparallel to the shear plane. Stage 2a: the intra-layer shear band cleavages were progressively developed and rotated toward the shear plane, while the angle (η) between the S-foliation and the cleavage was sub-stable. Stage 2b: the intra-layer shear band cleavages were intensely developed but were not much rotated toward the shear plane, while the angle (η) between the S-foliation and the cleavage decreased. (C) Stage 3: the inter-layer shear band cleavages were developed, where the angles (ψ) between the shear plane and the intra-layer shear band cleavages tend to be larger (i.e. Fig. 9). Where the inter-layer shear band cleavages occur, the intra-layer shear band cleavages became largely or completely inactive.

568 Figure 12. Diagrams for comparing between the rotation of several material lines of
 569 strain ellipse in simple shear on a model presented in this paper and the data in Fig.
 570 10. Shear strains were calculated from the angle (ϕ) between the S-foliation and
 571 the shear plane according to two assumptions: (i) ϕ being the material line of a
 572 simple shear strain ellipse and the initial angle of the material line: $\phi_0 = 60^\circ$ (broken
 573 lines for theoretical calculation and open triangles for the data) and (ii) ϕ being the
 574 long axis of the simple shear strain ellipse (solid lines for theoretical calculation
 575 and solid circles for the data). Δ represents the proportion of the bulk simple
 576 shear strain (γ). See text for discussion.

Figure1

Figure 1: Michibayashi and Murakami

Figure2

Figure 2: Michibayashi and Murakami

Figure3

Figure 3 : Michibayashi and Murakami

Figure5

Figure 5 : Michibayashi and Murakami

Figure 6: Michibayashi and Murakami

Figure7

Figure 7 : Michibayashi and Murakami

Figure8

Figure 8 : Michibayashi and Murakami

Figure9

Figure 9 : Michibayashi and Murakami

Figure10

Figure 10: Michibayashi and Murakami

Figure

Figure 4: Michibayashi and Murakami

Figure11

Figure 11: Michibayashi and Murakami

Figure12

Fig. 12: Michibayashi and Murakami