Development of quartz ribbons in quartzofeldspathic granulites

NIBIR MANDAL[1], KIYOSHI FUJINO[2] and SUSANTA K SAMANTA[1]

[1]*Department of Geological Sciences, Jadavpur University, Calcutta 700 032, India*
[2]*Department of Earth and Planetary Sciences, Hokkaido University, Sapporo 060, Japan*

In high-grade (granulite facies) quartzofeldspathic rocks the progressive development of a fabric records contrasting deformation behaviour of quartz and feldspar. Feldspar has undergone deformation mainly by recrystallization-accommodated dislocation creep and produced smaller recrystallized grains progressively in the course of deformation. Quartz has not deformed solely by dislocation creep but also by a diffusion-controlled mechanism. Dislocation climb is important in the dislocation creep of quartz. In contrast to feldspar, quartz grains have not recrystallized into smaller grains at any stage of deformation. Rather, they have transformed initially to short monocrystalline ribbons and ultimately to long polycrystalline ribbons. This textural change of quartz is a continuous process and has taken place in the course of bulk textural change of the rocks during the deformation.

1. Introduction

In some deformed rocks, quartz occurs as exceptionally long grains, forming ribbon-like structures (Christie 1963; Wilson 1975; Mitra 1978; Law *et al* 1984). On the basis of geometry, the ribbon structures have been classified into different types (Boullier and Bouchez 1978). It is now understood that quartz ribbons are of diverse origin. The origin of ribbons by large crystal-plastic deformation has been most widely documented (Ramsay and Huber 1983; Twiss and Moores 1992; Ghosh 1994). However, a grain can also stretch plastically to a very long shape without synkinematic recrystallization. This can happen only in specific deformation conditions. In experiments (Hirth and Tullis 1992), the original grains undergo large flattening in deformation under moderate strain rate and temperature condition (Regime 2). Analytical studies (Jessell 1988) indicate that a long shape fabric may evolve by coalescence of grains through grain boundary migration. Such shape fabrics will not develop if subgrain formation becomes important during the initial stage of deformation.

During the deformation of quartz grains by dislocation creep, deformation bands sometimes form parallel to the elongation direction of the grains and the grains split along the deformation bands, forming ribbon-like structures (Tullis *et al* 1973; Hobbs *et al* 1976). This mode of ribbon formation is, however, to be distinguished from that resulting from a continuous elongation of the original grains (Burg 1986; Hirth and Tullis 1992).

Quartz ribbons have been reported from high-temperature (amphibolite or higher metamorphic grades) deformation conditions (Culshaw and Fyson 1984; McLelland 1984). They are generally polycrystalline and the individual crystals apparently do not show any intracrystalline strain under the optical microscope. Their origin is not clearly understood. It has been suggested (Culshaw and Fyson 1984) that such ribbons form during a concluding phase of deformation by oriented grain growth of dynamically-recrystallized early grains. Passchier and Trouw (p. 107, 1996) relate the development of ribbons in quartzofeldspathic mylonites to synkinematic diffusional processes and grain boundary migration.

We have recorded quartz ribbons in garnet-bearing quartzofeldspathic rocks (leptynite, Sen 1987) from the Eastern Ghats granulite belt, India. The quartz ribbons occur along a pervasive planar fabric in the

Keywords. Quartz ribbons; deformation; dislocations; recrystallization.

rocks. The pressure and temperature conditions in which the fabric had developed, have been constrained to be about 5–6 kb and 900°C (Karmakar 1992). In the rocks, quartz and feldspar show contrasting textural changes; the feldspar grains have recrystallized into smaller grains, whilst the quartz grains have transformed to ribbon structures. With the help of microstructural analysis, we have made an attempt to trace the course of development of the quartz ribbons.

The present study indicates that the ribbons have developed in the course of bulk textural changes of the rocks during deformation.

2. Textural description

2.1 *Mineralogical composition*

Quartz and alkali feldspar are the principal minerals of the rocks constituting more than 60% by modal volume. Alkali feldspars are generally perthitic, with exsolution lamellae of albite occupying over 40% (by volume) of the grains. The rocks characteristically contain garnet (as much as 20% by volume). In some of the rocks, biotite and plagioclase are also present (0–15%). The other minerals which occur as minor phases are rutile, apatite and spinel. Rutile occurs mostly as inclusions in the quartz and feldspar grains.

2.2 *Fabric*

Quartz ribbons are set in a matrix of small (5–8 µm) feldspar grains, and aligned along a planar fabric, recognizable both in the mesoscopic and microscopic scales. The fabric is defined by strongly flattened feldspar porphyroclasts, with size varying from a few tens of microns to a few centimetres, and lenticular quartz grains. Biotite grains, when present in the rock, are also aligned along the fabric. Exsolution lamellae in feldspar porphyroclasts often show microfolds with axial planes parallel to the fabric. On the mesoscopic scale, the fabric has a lineation parallel to the elongation direction of large feldspar porphyroclasts. From the occurrences of flattened and stretched feldspar porphyroclasts and axial planes of microfolds of exsolution lamellaes within feldspars, we can assume that the planar and linear fabrics in the rocks have formed respectively parallel to the XY principal plane and the principal extension direction (X) of the finite strain. The quartz ribbons are consistent in

Table 1. *A generalized scheme for the textural variation in the rocks.*

SCHEME OF TEXTURAL CHANGE

QUARTZ	FELDSPAR	OVERALL TEXTURE
NO PREFERRED SHAPE (No recrystallization)	NO PREFERRED SHAPE (Grain boundary recrystallization)	MOSAIC OF QUARTZ & FELDSPAR GRAINS; PROPORTION OF RECRYSTALLIZED SMALLER FELDSPAR GRAINS ABOUT 5 %
PREFERRED ORIENTATION OF GRAINS; OCCURRENCES OF SHORT RIBBONS (Aspect ratio <5) (No recrystallization into smaller grains)	ELONGATE ORIGINAL FELDSPAR GRAINS ; DEFORMED EXSOLUTION LAMELLAE (Grain boundary recrystallizatioin continued)	ORIGINAL GRAIN BOUNDARIES PARTLY REPLACED BY SMALL RECRYSTALLIZED FELDSPAR GRAINS; SHAPE FABRIC DISCERNIBLE
MONOCRYSTALLINE RIBBONS; RIBBONS WITH DEFORMATION BANDS AND SHORT GRAINS (ASPECT RATIO 5-8)	STRONGLY FLATTENED PORPHYROCLASTS IN THE MATRIX OF RECRYSTALLIZED SMALL GRAINS	ORIGINAL GRAIN BOUNDARIES ALMOST DESTROYED; PROPORTION OF RECRYTALLIZED FELDSPAR ABOVE 60%
VERY LONG POLYCRYSTALLINE RIBBONS (ASPECT RATIO > 10)	FELDSPAR PORPHYROCLATS REDUCED IN SIZE AND PROPORTION	RIBBONS IN THE MATRIX OF SMALL RECRYSTALLIZED FELDSPAR GRAINS (<80%);

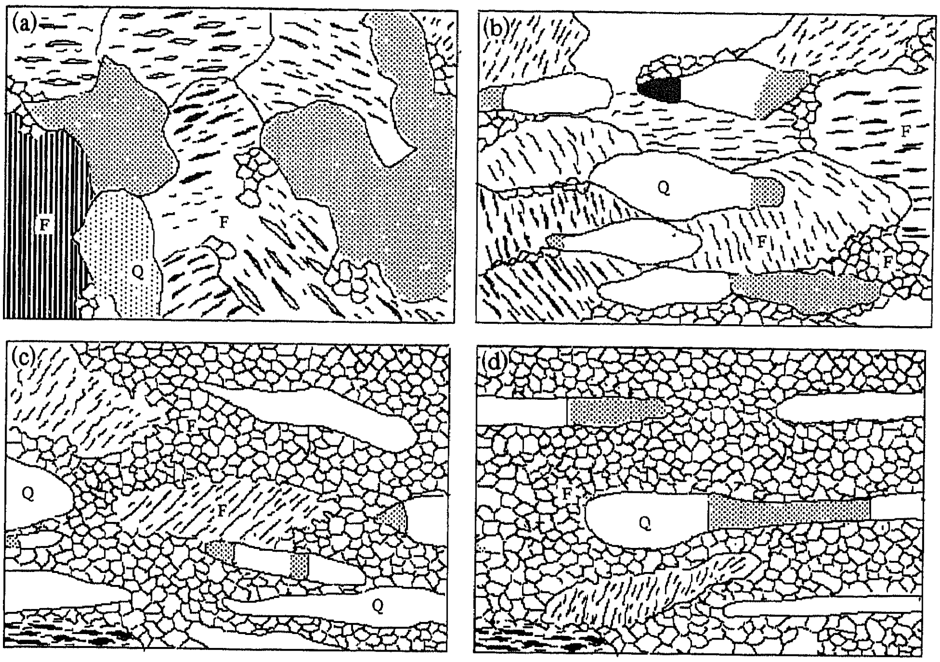


Figure 1. Textural variations in quartzofeldspathic rocks. From (**a**) to (**d**) the rocks mesoscopically grade from massive variety to foliated ones. Q = Quartz, F = Feldspar (sketches from optical thin sections; horizontal length of sketch area represents 2 mm).

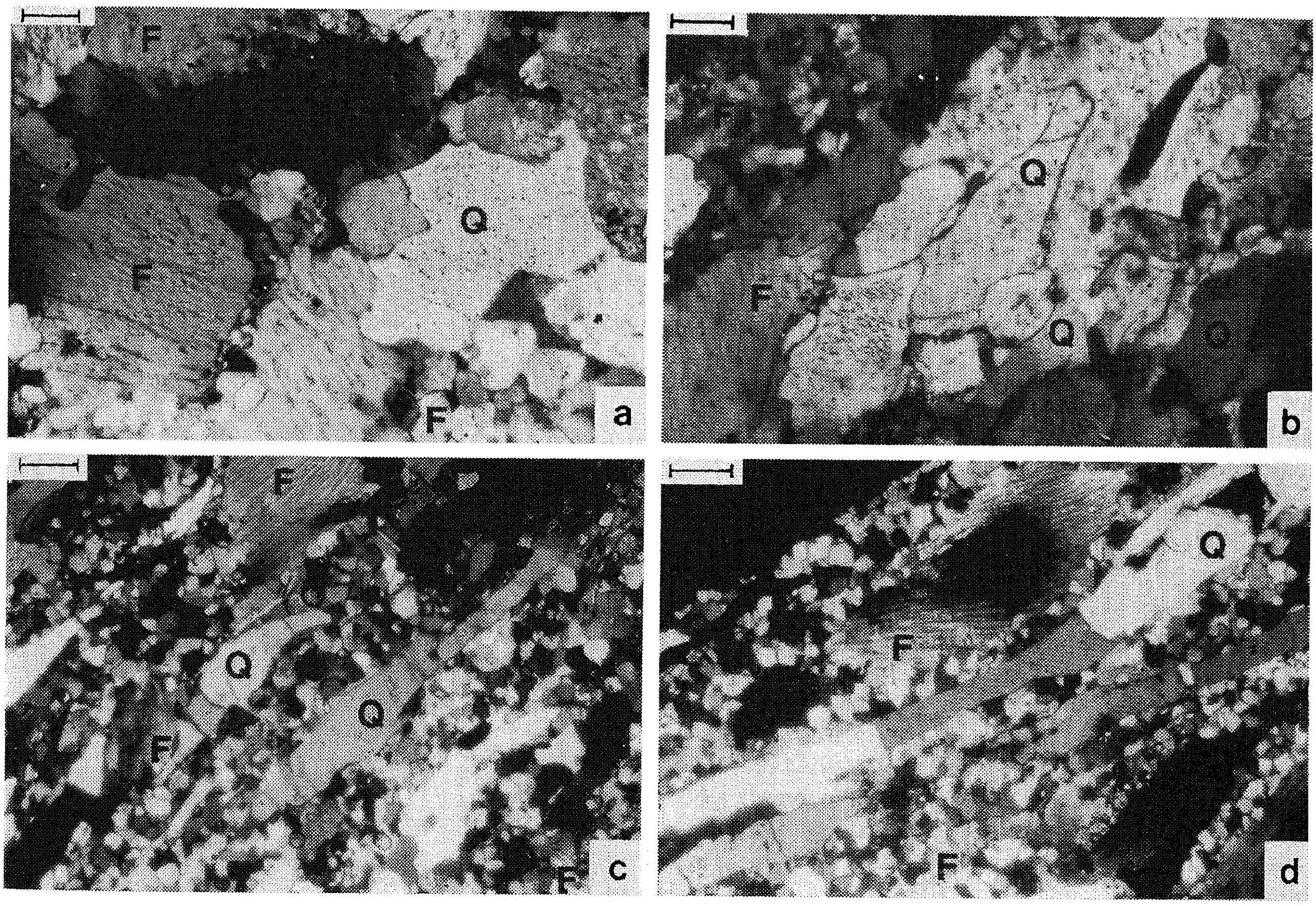


Figure 2. Textural transformations of quartz (Q) and feldspar (F) in the course of development of fabric in the rocks. (Scale bar = 0.02 mm).

orientation with the linear fabric, and thus correlate with the principal extension direction (X) of the deformation.

2.3 *Progressive development of textures*

The development of the fabric in the rocks is spatially heterogeneous. Along a field traverse of about one kilometer we found a variation from a massive rock to one with a strong fabric. This variation is also reflected in the microstructures and it has been possible to establish the textural development of the rocks (table 1).

The texture of the massive rocks is characterized by a mosaic of quartz and feldspar (figures 1a and 2a) where both the minerals do not have any strong dimensional orientation. Feldspar grains show undulatory extinction, and are associated with narrow zones of dynamically recrystallized grains at the grain boundaries. In contrast, quartz shows relatively weak undulatory extinction and no sign of dynamic recrystallization or subgrain formation either at the grain boundaries or within the grains (figure 2a).

In rocks with a somewhat stronger fabric, feldspar grains have recrystallized to a greater extent, producing further smaller grains, and have a preferred elongation (figure 1b). Quartz grains also have a preferred elongation in the same orientation (figure 2b) and show undulatory extinction, but there is still no sign of dynamic recrystallization into smaller grains. At this stage, quartz occurs in three modes: elliptical inclusions in feldspar grains (figure 3a), lenticular grains partly bounded by original feldspar grains (figure 3b), and ribbons (aspect ratio $\approx$ 3–5 : 1) confined mostly by recrystallized smaller feldspar grains (figure 3c). Large quartz grains adjacent to original feldspar grains show relatively strong undulatory extinction. Some lenticular grains or ribbons have deformation band-like structures oriented at a high angle to the elongation direction (figure 2b) and small grains, with boundaries along deformation bands.

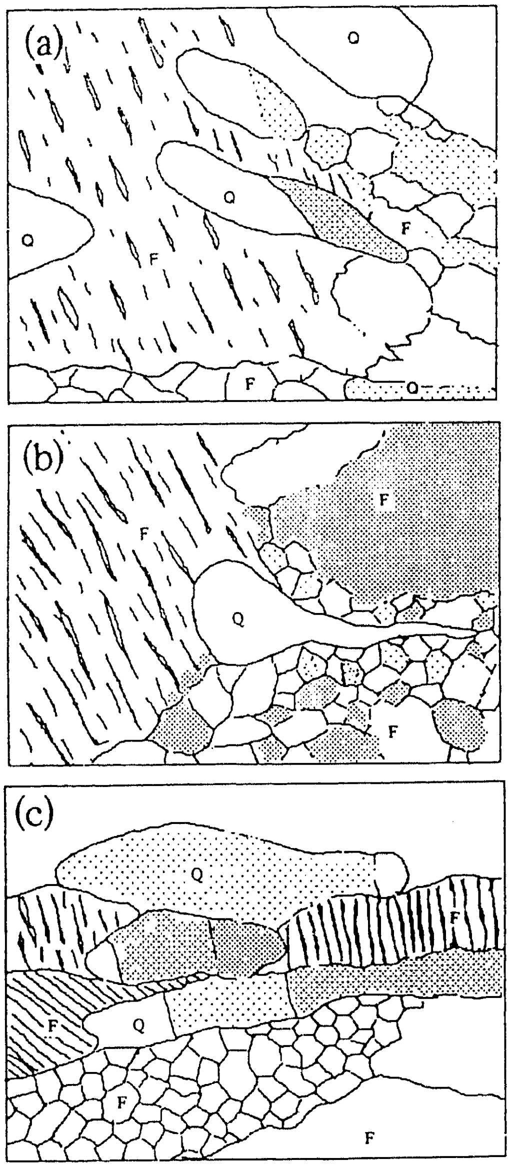


Figure 3. Different modes of occurrences of quartz in an intermediate-stage textural setup.

In rocks with a strong fabric, the proportion of recrystallized feldspar is very high, occupying about 60% by area in thin sections and the original grain boundaries are almost obliterated (figure 2c). Original feldspar grains occur as isolated elongate porphyroclasts within this matrix (figure 1c). Quartz shows neither an increase in internal strain nor a tendency to recrystallize into smaller grains. Rather, some long quartz grains that are entirely confined by recrystallized feldspar grains show approximately uniform optical extinction. The ribbons generally consist of a small number (2–3) of short grains or deformation bands (figure 2c).

In the most deformed rocks, smaller recrystallized feldspar grains constitute almost the entire (80%) texture, with only a few original feldspar grains occurring sporadically as porphyroclasts (figure 1d). Quartz also shows a conspicuous change in its mode of occurrence. Short monocrystalline ribbons are reduced in number, with a complementary increase in the proportion of very long ribbons (aspect ratio $> 10:1$) (figures 2c and d). The long ribbons often wrap around remnant feldspar porphyroclasts and show bending folds in pinch-and-swells in garnet grains (figures 11f and g).

2.4 *TEM observations*

We prepared specimens for TEM analysis from thin sections, cut perpendicular to the planar fabric and parallel to the lineation (i.e., XZ sections). Quartz grains representative of the successive stages of textural development, from weakly flattened grains

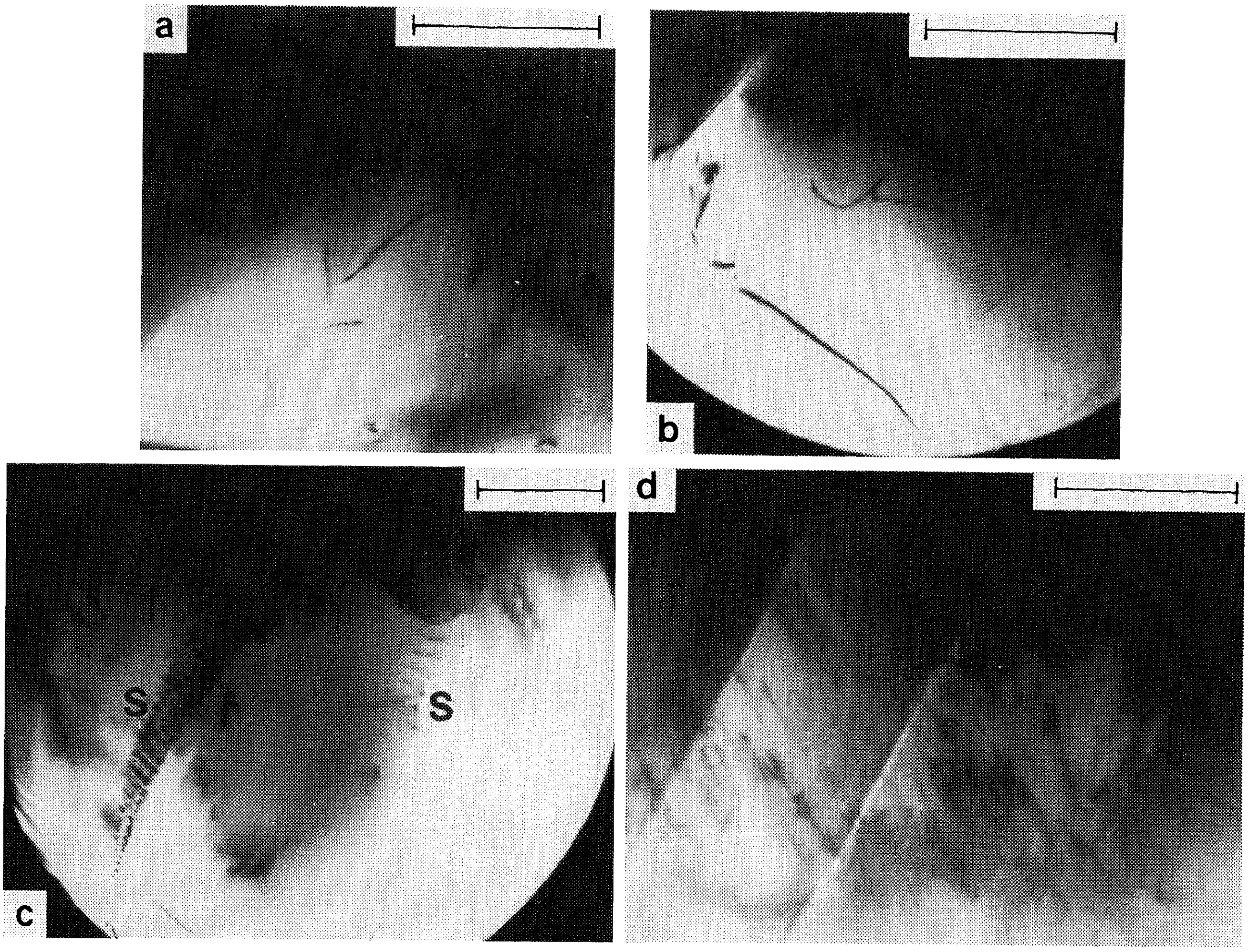


Figure 4. TEM micrographs of quartz and feldspar. (**a**) and (**b**) Free dislocations in quartz, (**c**) Curved dislocation arrays (S) in weakly flattened quartz (**d**) Dislocations in feldspar. (Scale bar = 1 μm).

to ribbons, were studied systematically. The density of free dislocations in quartz in all stages is low ($\approx 1 - 6 \times 10^8/\text{cm}^2$).

Quartz in the initial-stage texture of the rocks shows an association of curved and straight dislocations and dislocation arrays (figures 4a and b). The dislocation arrays are diversely oriented and some of them are curved, with varying orientation of dislocations in the array (figure 4c). The latter is similar to type 2 sub-boundaries of Bouchez *et al* (1984). Subgrains were not observed in any of the specimens.

The dislocation structures in short (aspect ratio 3–5) monocrystalline ribbons (figure 5a) are more or less similar to the above. However, the dislocation density is somewhat higher ($6.13 \times 10^8/\text{cm}^2$). Straight dislocation arrays occurring in a parallel arrangement (figure 5b) are an additional feature.

The dislocation structures in very long (aspect ratio > 10) ribbons are not also drastically different. Curvilinear dislocations are associated with straight dislocations of uniform orientation (figure 6a). The free dislocations often form large semiloops (figure 6b). Dislocation arrays have rarely been observed. The dislocation density of the long polycrystalline quartz ribbons ($1.45 \times 10^8/\text{cm}^2$) has slightly decreased in the transition from short monocrystalline ones.

2.5 *Analysis of textures*

Quartz and feldspar show contrasting deformation behaviours. Strongly undulatory extinction, deformed exsolution lamellae (figure 7a), oriented and boudinaged rutile needle inclusions and extreme grain-boundary recrystallization (figure 7b) in feldspar, indicate that deformation was dominated by crystal-plastic mechanisms. Both the intergranular and intragranular strains were heterogeneous, and this has led to recrystallization into smaller grains (figure 7a). Quartz grains show weakly undulatory extinction and the rutile inclusions in quartz have, though weak, a distinct preferred orientation. In addition, some elongate grains and short ribbons have deformation bands. These textural features certainly indicate that quartz has also participated in crystal plastic deformation. However, quartz does not follow the same

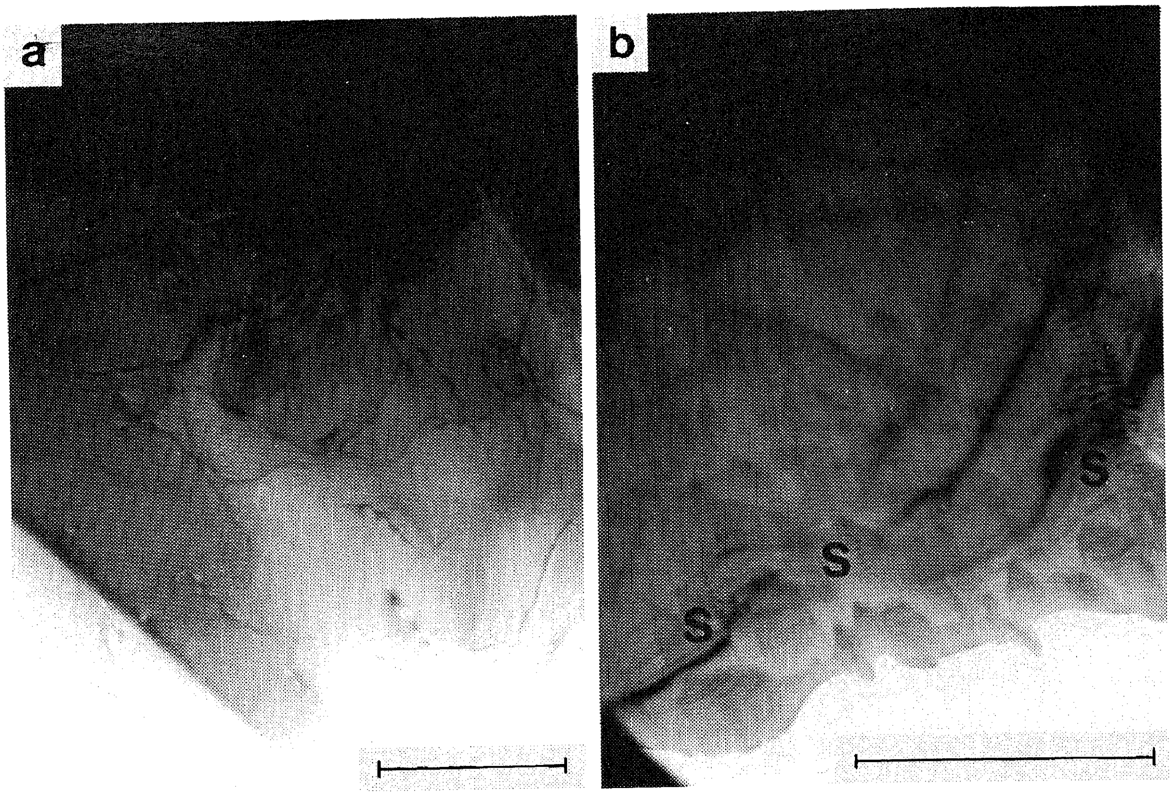


Figure 5. TEM micrographs of short ribbon quartz. (a) Curvilinear free dislocation arrays (S), (b) Parallel arrangement of dislocation arrays (S). (Scale bar = 1 μm).

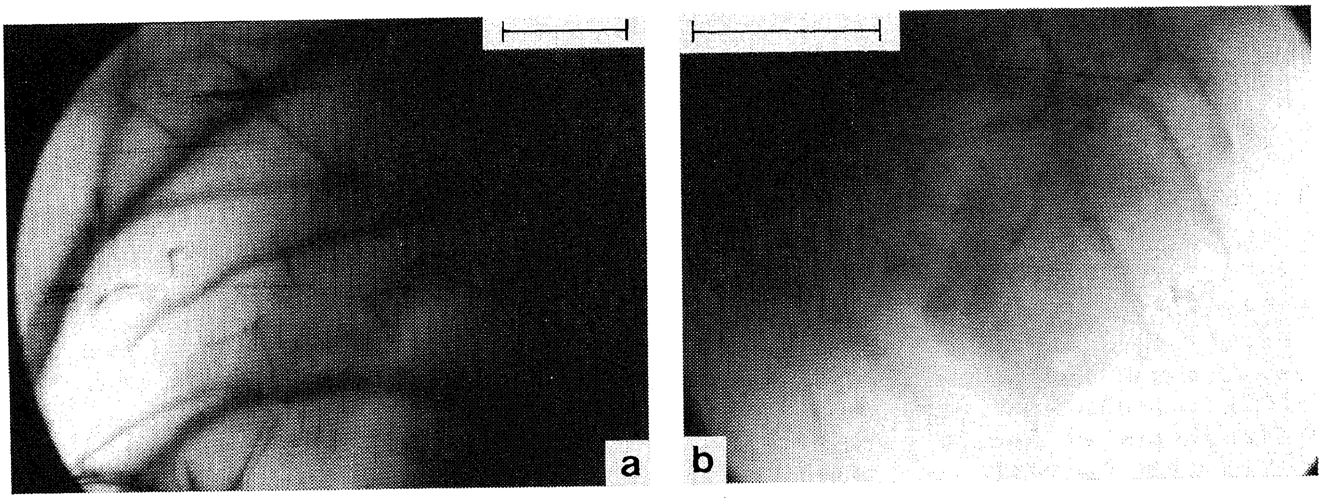


Figure 6. TEM micrographs from a very long quartz ribbon (a) Free dislocation distribution (b) Dislocation semiloops. (Scale bar = 1 μm).

textural change as feldspar. The intragranular strain of quartz is more homogeneous, and not associated with significant subgrain formation or recrystallization at any stage of deformation. Furthermore, quartz has deformed not simply by crystal-plastic mechanism. The following observations suggest that quartz deformation has also involved a diffusion-controlled deformation mechanism:

(1) Some elongate grains, containing inclusions, have inclusion-free fringes at the extensional faces (figure 7c). (2) Elongate quartz grains show sharp contacts with feldspar at the faces, parallel to the fabric. The traces of recrystallized feldspar grains can often be seen within quartz ribbons (figure 7d). (3) Strongly flattened small grains, often occurring as inclusions in feldspar, show much less internal strain optically compared to very large quartz grains (figure 7a). The difference between quartz and feldspar deformation behaviour is indicated from the contrast in orientation distribution of rutile needle

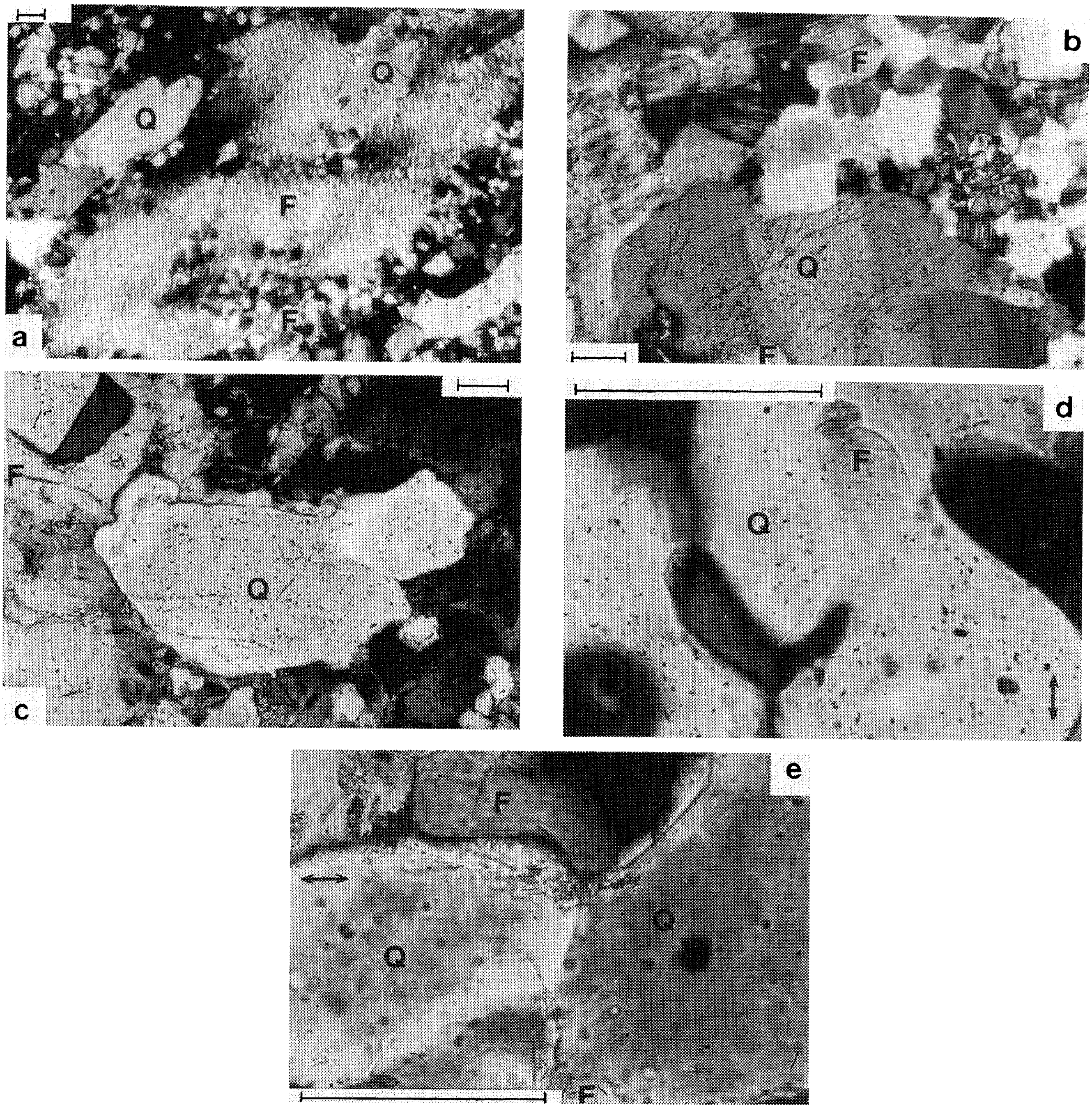


Figure 7. Deformations of quartz(Q) and feldspar(F). (**a**) Deformed exsolution lamellae in feldspar porphyroclast. Note that the recrystallization is significant in feldspar while absent in the equally flattened quartz inclusions, (**b**) Large quartz grains with weak undulatory extinction. In contrast to feldspar, it is not recrystallized into smaller grains, (**c**) Inclusion-free fringes at the extensional faces in quartz grains, (**d**) Relics of recrystallized feldspar grains in quartz ribbon and (**e**) Coalescence of quartz ribbons across feldspar grains. ↔ indicates the lateral extension of the ribbon.(Scale bar = 0.01 mm).

inclusions (figure 8). For equally flattened quartz and feldspar grains in a section, the orientation dispersion of rutile inclusions in quartz is much wider than that in feldspar. However, the reorientations of rutile inclusions might have been influenced by other factors, such as anisotropism in the minerals.

The TEM observations and micro-structures indicate that both quartz and feldspar have undergone a dislocation creep, but by contrasting mechanisms. The presence of semi-loops, or curvilinear dislocations, dislocation arrays and low average dislocation density in quartz indicate that dislocation climb was likely to be efficient in the deformation of quartz. In contrast, a higher density of dislocations in feldspar (figure 4d) and the microstructures (figures 7a and b) indicate that grain-boundary migration recrystallization has

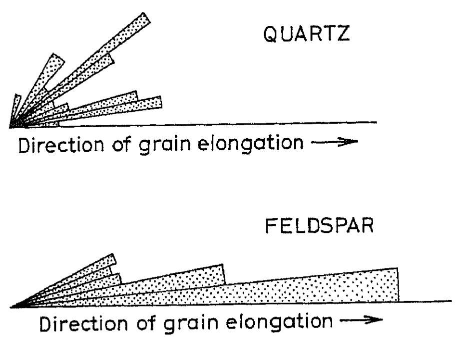


Figure 8. Orientation dispersions of rutile inclusions in quartz and feldspar. (Angular division = 5°; Radius 1 cm = 15%).

acted as the accommodation mechanism in the feldspar deformation (recrystallization-accommodated dislocation creep, Yund and Tullis 1991).

3. Quartz ribbons

3.1 *Ribbon geometry*

The textural features of the quartz ribbons are similar to those described by Culshaw and Fyson (1984). In the present case, we can categorize the ribbons into three types: lenticular monocrystalline ribbons; lenticular ribbons with deformation bands or short grains; and very long polycrystalline ribbons. Lenticular monocrystalline ribbons (figure 9a) are short in length and their aspect ratio varies in the range of 3 to 5. They generally show weak internal strain optically. The lenticular ribbons sometimes have deformation bands, and short grains, with their width varying from the centre to the edge of the ribbon (figures 9b and c). The deformation bands and boundaries of short grains are at a high angle to the ribbon wall. In some of the ribbons, there is a close association of deformation bands and short grains. The width of deformation bands and short grains increases linearly with the ribbon thickness (figure 10), and have an average aspect ratio of 1 : 3.

The long ribbons (aspect ratio > 10 : 1 figure 9d) are mostly polycrystalline. However, the number of grains in a ribbon is always small. The grains are rectangular in cross section, and have large length to width ratios (4–6). Most of them apparently do not show internal strain optically. The grain boundaries are at a right angle to the ribbon wall.

Long quartz ribbons show diverse textural relationships with the feldspar grains (figure 11). Typically, straight quartz ribbons occur in the matrix of small recrystallized feldspar grains (figures 2d, 9d and 11a). The ribbon walls sharply truncate the feldspar grains. Occasionally, aggregates of small feldspar grains occur as a bar in the ribbons (figure 11b). Again, two ribbons are separated by a thin wall of original feldspar grains (figures 9d and 11c). Some ribbons occurring along a line, have feldspar grains, forming a wedge-like bridge, in between two ribbons (figure 11d). The ribbons are not always uniform in thickness, and seem to have formed by linking a number of consecutive lenticular ribbons through narrow passages across feldspar grains (figures 7e and 11e).

3.2 *Stages of development of quartz ribbons*

We made an analysis for the variation of quartz ribbon geometry with the flattening of feldspar porphyroclasts. The aspect ratio of ribbons increases consistently with that of the porphyroclasts (figure 12). Also, in the course of deformation the proportion of feldspar porphyroclasts has decreased with a complementary increase in the recrystallized smaller grains, and with this textural change, a variation in the ribbon type is noticed. This evidence indicates that the textural change of quartz (from large equidimensional grains to ribbons) is a continuous process and has taken place during the development of fabric in the rocks. In the following section, we summarize the successive stages of development of the ribbon structures (table 2).

Stage 1: Quartz ribbons are monocrystalline and short in length. They are bounded by original grains and partly by smaller recrystallized feldspar grains. Weak undulatory optical extinction is noticed in the majority of ribbons. The aspect ratio of ribbons slightly increases with that of feldspar porphyroclasts (figure 12). Some short ribbons, occurring as inclusions in feldspar, have aspect ratios close to that of feldspar porphyroclasts (figure 12). These features suggest that the ribbons have formed by progressive flattening of original quartz grains. The substructures, such as curved dislocations, dislocation walls (figures 4a and c), in ribbon quartz indicate that dislocation climb is important in this stage of ribbon formation.

Stage 2: Quartz ribbons are mostly bounded by smaller recrystallized feldspar grains. The ribbons become somewhat longer (aspect ratio in average is about 5) and regular deformation bands form in some of the ribbons. From the deformation bands (figure 9b), the dislocation creep is still evident in this stage of ribbon formation. Parallel straight dislocation arrays are a typical substructure (figure 5b). In the domains of strongly heterogeneous strain, the deformation bands split, forming short grains in the ribbons (figure 9c).

Stage 3: The original grain boundaries are entirely obliterated by the grain boundary recrystallization in feldspar. The quartz ribbons occur in the matrix of smaller recrystallized feldspar grains. The lenticular ribbons are replaced by very long ribbons (aspect ratio > 10), and the aspect ratio of the ribbons steeply increases (figure 12). The ribbons often have thin walls of feldspar (sometimes cut-off)

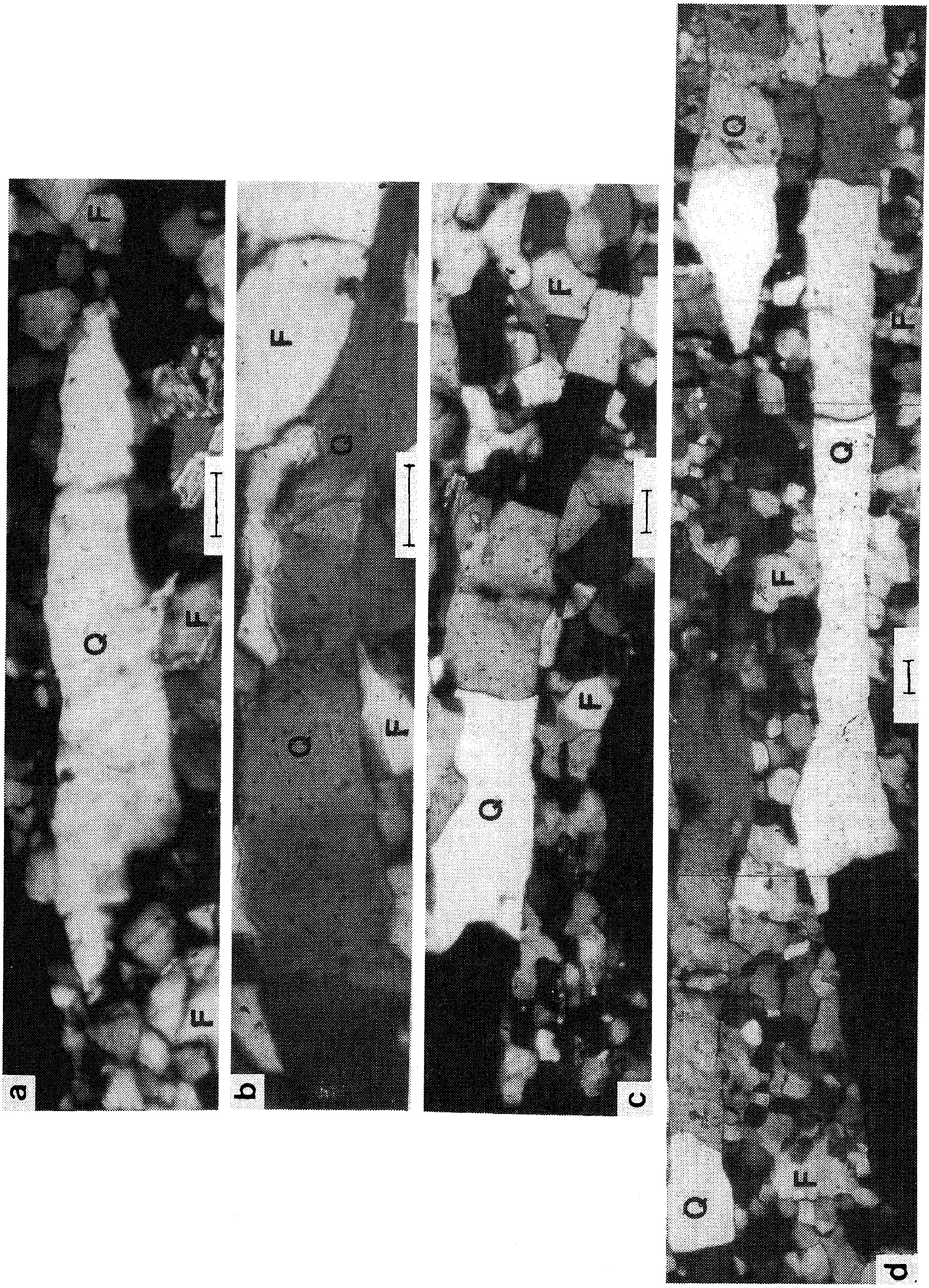


Figure 9. Ribbon geometry: (**a**) lenticular monocrystalline ribbon, (**b**) lenticular ribbons with deformation bands (note the variation in the band-width from the centre to edge of the ribbon), (**c**) ribbon with short grains and (**d**) very long polycrystalline ribbon. Note deformation bands as relics (upper right) in (d). (Scale bar = 0.05 mm).

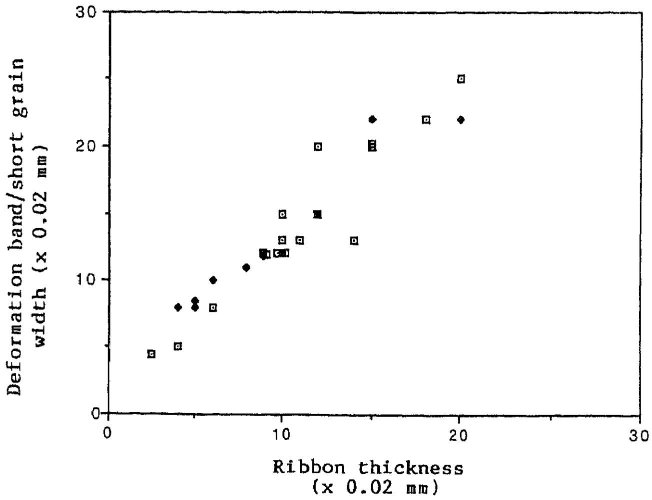


Figure 10. Linear variation of the width of deformation bands (open square with dot) and short grains (solid rhomb) with ribbon thickness.

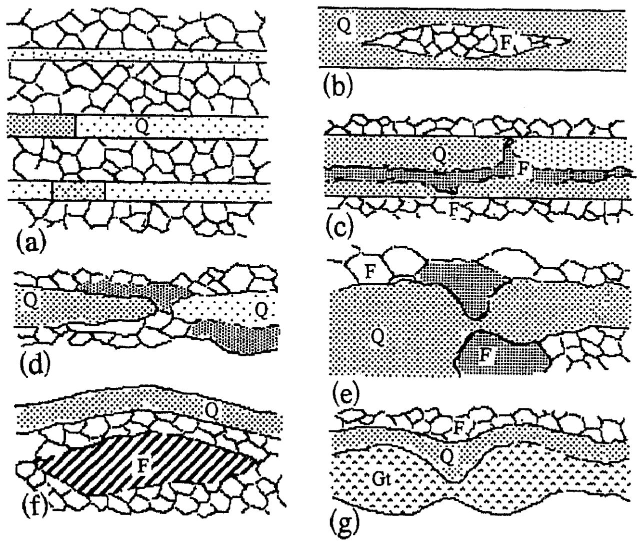


Figure 11. Different textural relationships of long ribbons (Q) with feldspar (F) and garnet (Gt).

at a right angle to the ribbon wall and inclusions of recrystallized feldspar grains (figures 7d and e). These features indicate that lenticular ribbons might have coalesced with one another and formed the long ribbons.

The coalescence of ribbons is (figure 7e) the prime process in this stage of ribbon formation. However, since there is no drastic change in the substructures, we assume that the dislocation creep continues in this stage. From the microstructures of long ribbons, such as drags around feldspar porphyroclasts and bending folds in pinch-and-swells in garnet grains, (figures 11f and g) an active deformation in this stage is also evident.

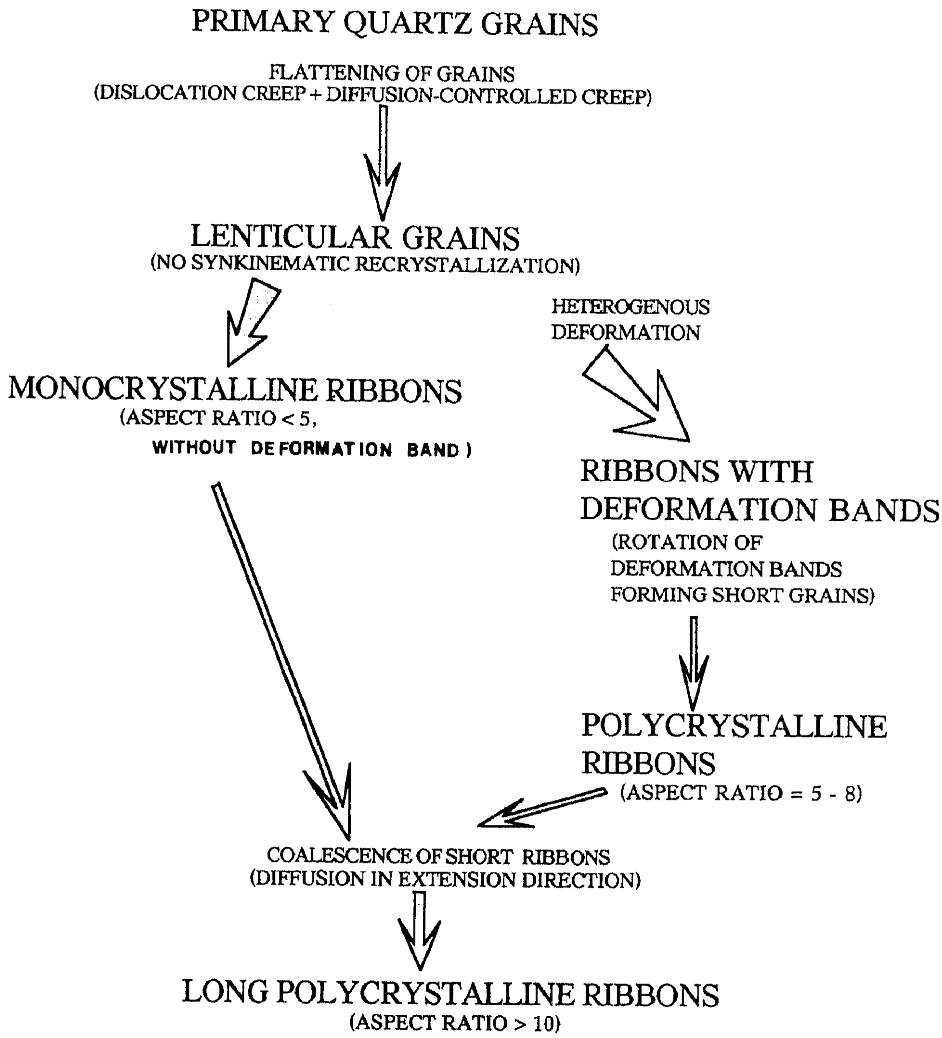
4. Discussion

The contrasting textural association of quartz (ribbon) and feldspar (small recrystallized grains) is a result of the difference in deformation behaviour between the two minerals. Feldspar has undergone deformation by dislocation creep and accompanying grain-boundary recrystallization. Deformation bands and dislocation structures in quartz certainly indicate that quartz also has deformed by dislocation creep. But, quartz has not recrystallized into smaller grains in any stage of deformation. The non-concurrence of recrystallization in quartz may be due to the recovery by annihilation of free dislocations by climb. The dislocation climb is indeed evident from the substructures (figures 4c and 5). Generally, heterogeneities (in grain-scale) in deformation promote dynamic recrystallization (Drury and Urai 1990). In the present case, compared to feldspar, quartz grains have deformed more homogeneously in the matrix of recrystallized smaller feldspar grains. This may be another reason for the non-concurrence of recrystallization in quartz. The phenomenon is somewhat similar to deformation of quartz aggregates in dislocation creep regime 2 of Hirth and Tullis (1992).

The short grains in a ribbon are generally described as remains of dynamically recrystallized early grains (Culshaw and Fyson 1984). In the present case, they seem to have a different origin. Their close geometrical similarity and association with the deformation bands (figure 10) indicate that they have formed by splitting of the ribbons along the boundaries deformation bands. The short grains are most abundant in an intermediate stage of the textural change. Since the texture consists of partly original grain boundaries and partly recrystallized grains, the deformation in the micro-scale is locally heterogeneous, and this probably have caused the deformation bands to rotate to a large extent and form short grains.

Long (aspect ratio > 10) ribbons are well developed in the domains where the original grain boundaries have been entirely obliterated by the grain boundary recrystallization in feldspar. Relics of original grains and recrystallized grains of feldspar often occur in the long ribbons. In some places, lenticular ribbons are connected through narrow passages across feldspar grains. From this textural evidence, lenticular grains and short ribbons seem to have coalesced along the extension direction (figures 7d and e), forming long polycrystalline ribbons. This is also evident from a steep increase in the aspect ratio of ribbons in the transition between short monocrystalline and long polycrystalline ribbons (figure 12). However, it is not clearly understood how the quartz grains might have replaced feldspar to make the avenues and coalesced with one another. It has been found that the grain boundaries are mobile in high-temperature

Table 2. *Course of development of long polycrystalline quartz ribbons.*



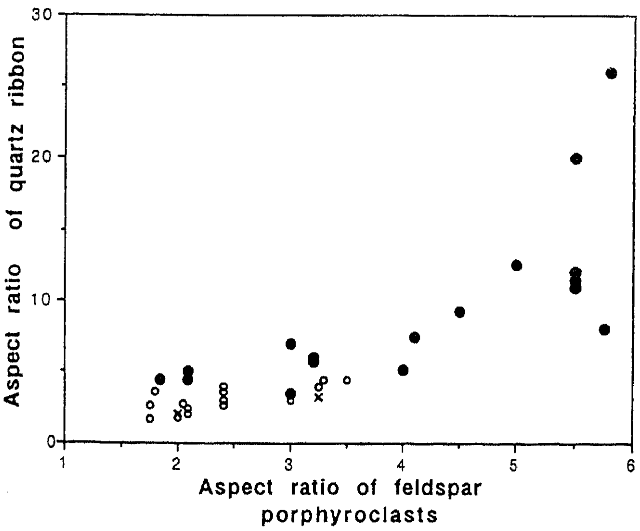


Figure 12. Plot of the aspect ratios of quartz ribbons versus that of feldspar porphyroclasts. Open circles, solid circles and crosses denote monocrystalline ribbons, polycrystalline ribbons and quartz inclusions in feldspar, respectively.

deformation of quartz-feldspar aggregates (Gower and Simpson 1992). By grain boundary migration in a preferred direction (extension direction) adjacent quartz grains might have come in contact with one another.

We sum up the course of development of the quartz ribbons as follows (table 2): the initial grains deform by a combination of crystal-plastic and secondary, possibly diffusion-controlled, creep. The dislocation climb is the efficient recovery process to keep the dislocation density low. The progressive flattening of the original grains leads to the formation of short lenticular monocrystalline ribbons or ribbons with deformation bands (aspect ratio 3:5). In micro-domains of strongly heterogeneous deformation, the ribbons locally split into short grains. In advanced stages, when the original grain boundaries in the quartz-feldspar aggregates are almost destroyed and the original feldspar grains occur as islands in the matrix of smaller recrystallized grains, the lenticular ribbons coalesce with one another in the extension direction and give rise to long polycrystalline ribbons (aspect ratio even larger than 10).

Acknowledgements

The present work was supported by the Japan Society for the Promotion of Science and the Indian National Science Academy. We wish to thank N Tomioka, N Miyajima and S Shimmey for their help in the TEM study.

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