A Note on Deformation Bands in Quartz

By

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with 12 Text-figures

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ABSTRACT: Variation in width of deformation bands in quartz in four specimens collected from the Sangun crystalline schist of the Nakase district, Hyôgo Pref., and the Sambagawa crystalline schist of the Kôtsu district, Shikoku, has been examined. The band width is considerably variable. Within a restricted domain (e. g. each specimen), however, it is fairly constant, showing a single marked maximum (the most frequent width) in the variation diagram of the band width for each specimen. Both the most frequent width and the maximun width are different between four specimens, and the former is proportional to the latter, that is, the former increases with increase in the latter. The band width does not appear to be always dependent upon the grain size. The band width may be dependent upon the rate and temperature of deformation, that is, it may increase with increase in temperature and decrease in strain rate, as is the case of creep deformation of metalic crystals. The present knowledges of some other properties of the deformation bands in quartz are also briefly described and discussed.

Three types of syntectonic recrystallization of quartz which are also referred to three types of paracrystalline deformation of quartz have been distinguished as follows: 1) Type I ——— it is shown by polygonization of bending lattice (e.g. band-boundaries) and formation of new grains which do not show preferred lattice and dimensional orientation. 2) Type II ——— the shapes of recrystallized quartz grains are strongly elongated parallel to the direction of mass elongation of the system concerned but the reorientation of the c-axes (lattice) of those grains are scarcely induced. And 3) Type III ——— the formation of preferred lattice and dimensional orientation. Deformation bands do not appear to be formed in quartz grains giving rise to the syntectonic recrystallization of Types II and III.

CONTENTS

I. INTRODUCTION

Deformation bands in quartz are a planar structure terminating within the grain-boundaries, and they are displayed as narrow bands of different lattice orientation across the host crystal, showing a relation that, in each of the grain containing them, the change in the lattice orientation from the host to the band is in the same rotational sense. Some properties of the bands have so far been described and discussed by many authors. However, we have yet no available data on the band width. it appears to be considerably variable. Within a restricted domain, however, the bands appear to show usually fairly constant width. it is not understand what causes are related to the variation in the band width. The nature of the variation in width of the deformation bands in quartz will be examined in this paper. Some other properties of the bands examined in the previous papers will also be briefly sketched and discussed.

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II. DESCRIPTION and DISCUSSION

The band width is examined for the deformation bands in four specimens, among which two specimens were described with respect to some other features by the author (1961b ——— here termed specimen I; 1963 ——— specimen II) and the other two specimens are newly described in this paper (specimens III and IV). The specimen III is a deformed quartz vein in the Sangun crystalline schist of the Nakase district, Hyogo Pref., and the specimen IV is a deformed quartz vein in the Sambagawa crystalline schist of the Kôtsu district, Shikoku.

The crystallographic location of the deformation bands in the specimens I to IV can not directly be measured by the U-stage, but only their trends on the thin section can be measured. In the previous papers (HARA, 1961b, 1963 and 1964; HARA and NISHIMURA, 1965), the crystallographic location of the bands has been tentatively determined on the assumption that the axis of external rotation of the crystal lattice from the host to the band coincides with either the a-axis or the a*-axis, according to the knowledge of X-ray studies of naturally deformed quartz grains after HERITSCH *et al.* (1954), BAILEY *et al.* (1958) and PAULITSCH *et al.* (1963). It was also reproduced experimentally by CHRISTE *et al.* (1964) that both the a-axis and a*-axis were the axis of lattice bending in the deformed quartz. If the axis of external rotation from the host to the band coincides with a direction normal to the c-axis, the pole of band-boundary should lie on the plane containing the c-axis of the host and that of the band. In the specimen previously described by the author (1961a), the crystallographic location of the bands could be directly measured by the U-stage, like in the case of the experimentally produced deformation bands (CARTER *et al.* 1964; CHRISTIE *et al.*, 1964). In this specimen the angle between the pole of band-boundary ($L\perp$) and the plane containing the c-axis of the host (Ch) and that of the band (C_L) is very small (1961a, Fig. 9). Therefore, the above-assumption seem to be generally available to determine the width of natural deformation bands as well as their crystallographic location. On this belief, the band width will be determined in this paper.

Before the band width will be examined, some properties of the deformation bands in the specimens I to IV and other two specimens (HARA, 1964 and HARA and NISHIMURA, 1965) will be briefly sketched and discussed. In the $Ch \wedge L\perp$ histograms for the bands in those specimens (Figs. 1 and 2; HARA, 1961b, Fig. 6; 1963, Figs. 5-c, 6-c and 7-c; 1964, Fig. 8-c; HARA and NISHIMURA, 1965, Fig. 13-b), generally, the most significant maximum lies between 5° and 20°, indicating that many of the bands are inclined at low angles to the basal plane. This character of the crystallographic location of the bands is fairly similar to that of the deformation lamellae reported by SANDER (1930), FAIRBAIRN (1941), INGERSON and TUTTLE (1945), SAHA (1955), De ANIRUDDHA (1958), CHRISTIE ane RALEIGH (1958), HANSEN and BORG (1962), SCOTT *et al.* (1965), CARTER and FRIEDMAN (1965) and HARA (1963, 1964 and 1965). Strictly speaking, however, the deformation bands are inclined at lower angles to the basal plane than the deformation lamellae are (Figs. 3 and Carter *et al.* 1965, Fig. 5-b). In the CL∧L⊥

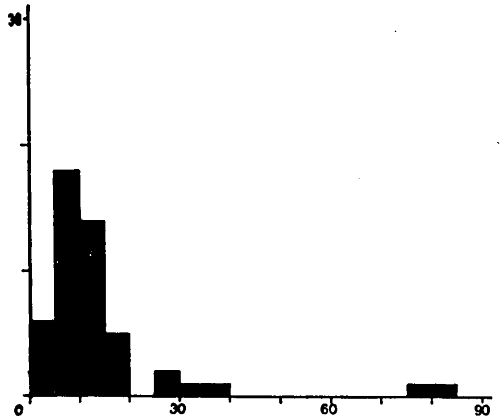

FIG. 1. Histogram showing the variation in the angle Ch∧L⊥ for the deformation bands in quartz in the specimen III. Frequency is given by number of grains.

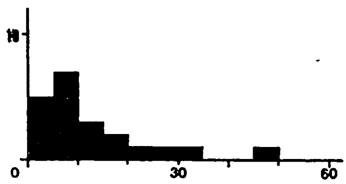

FIG. 2. Histogram showing the variation in the angle Ch∧L⊥ for the deformation bands in quartz in the specimen IV. Frequency is given by number of grains.

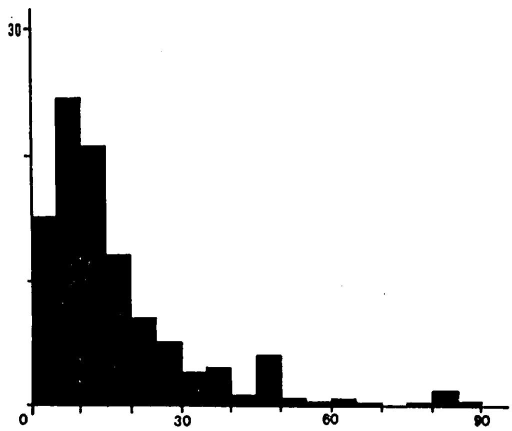

Fig. 3. Histogram showing the variation in the angle Ch∧L⊥ for the deformation bands in quartz in the six specimens (specimens I to IV and specimens described by HARA, 1964 and HARA and MISHIMURA). Frequency is given by percentage.

histograms for the six specimens (Figs. 4 and 5 ; HARA, 1961b, Fig. 7; 1963, Figs. 5-b, 6-b and 7-b; 1964, Fig. 8-b; HARA *et al.*, 1965, Fig. 13-c), generally, the most significant maximum lies between 0° and 15°. In the composite diagram for CL∧L⊥ in the six specimens (Fig. 6) there is a peak at between 0° and 5°. It can be noted that for many deformation bands the angle Ch∧L⊥ is larger than the angle CL∧L⊥. In the Ch∧CL histograms for the six specimens (Figs.7 and 8; HARA, 1961b, Fig. 8; 19 63, Figs. 5-a, 6-a and 7-a; 1964, Fig. 8-a; HARA *et al.*, Fig. 13-a), generally, the angle

Ch ∧ CL is smaller than 26°, and a marked maximum lies between 3° and 12°. In the composite diagram for Ch∧CL in the six specimens (Fig. 9) there is a peak at

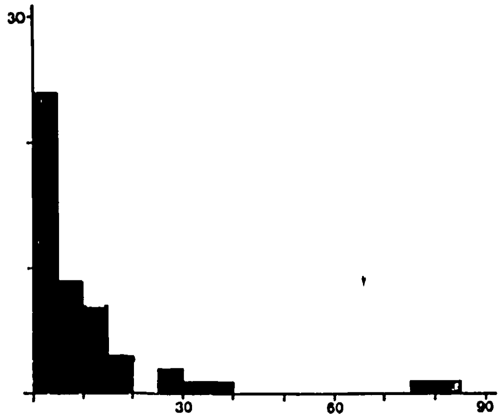

FIG. 4. Histogram showing the angle CL∧L⊥ for the deformation bands in quartz in the specimen III. Frequency is given by number of grains.

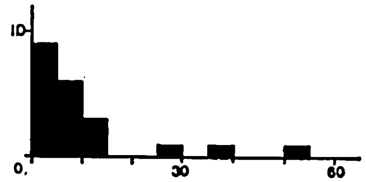

FIG. 5. Histogram showing the vaiation in the angle CL∧L⊥ for the deformation bands in quastz in the specimen IV. Frequency is given by number of grains.

FIG. 6. Histogram showing the variation the angle CL∧L⊥ for the deformation bands in quartz in the six specimens (specimens I to IV and specimens described by HARA, 1964 and HARA and NISHIMURA. 1965) Frequency is given by percentage.

between 4° and 8°. For the deformation bands in the specimens III and IV (Figs. 10 and 11) as well as those in other four specimens, it can further be noted that the bands are preferably oriented at two sets, which intersect at high angles to each other, and that the rotational sense of shift in the c-axis from the host to the band is the same for those belonging to the same set. According to the author (1961a) and the author *et al.* (1965), it will be said that the deformation bands are preferably oriented with an angle ca. 45° to the direction of the principal compressive stress, which would be related to the formation of the bands, and that CL (and L⊥ often) for most of the bands subparallel to the basal plane tends to lie nearer than Ch to the stress axis. The

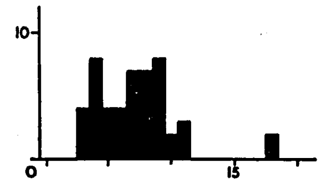

FIG. 7. Histogram showing the variation in the angle Ch∧CL for the deformation bands in quartz in the specimens III. Frequency is given by number of grains.

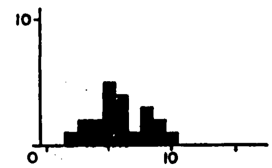

FIG. 8. Histogram showing the vriation in the engle Ch∧CL for the deformation bands in quartz in the specimens IV. Frequeny is given by number of grains.

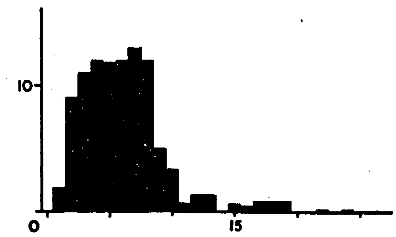

FIG. 9. Histogram showing the variation in the angle Ch∧CL for the deformation bands in quartz in the six specimens (specimens I to IV andspecimens described by HARA, 1964 and HARA and NISHIMURA, 1965).
Frequency is given by percentage.

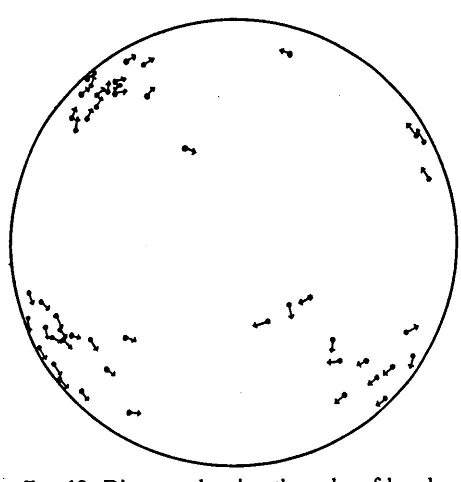

FIG. 10. Diagram showing the poles of band-boundaries (L⊥: solid circles) and the sense of lattice rotation from the host to the band (arrows) for the deformation bands in quartz in the specimen III.

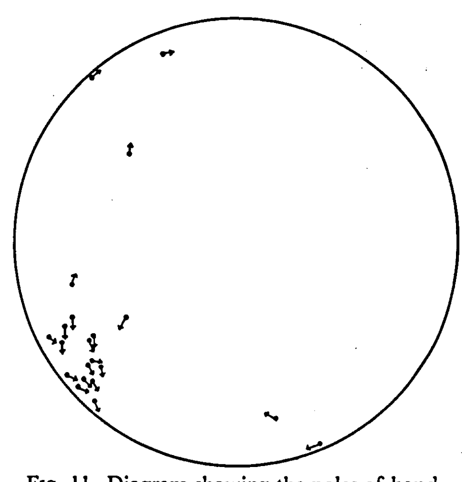

FIG. 11. Diagram showing the poles of band-boundaries (L⊥: solid circles) and the sense of lattice rotation from the host to the band (arrows) for the deformation bands in quartz in the specimens IV.

author's method for the dynamic analysis of deformation bands in quartz does not appear to be available for that of deformation lamellae. According to HANSEN and BORG (1962) and CARTER and FRIEDMAN (1965), the c-axes tend to lie nearer than the poles of deformation lamellae to the direction of the principal compressive stress, which would be related to the formation of the lamellae. Therefore, it can be pointed out that the positional relationship between Ch in any quartz grain and L⊥ in the same grain with reference to the stress system, which was deduced on the basis of twinning in calcite and that would have been related to the formation of the deformation bands and lamellae, is quite reverse between the bands and lamellae.

Recently, deformation bands in quartz were experimentally produced and analysed by CARTER *et al.* (1964) and CHRISTIE *et al.* (1964). Most of the experimentally produced deformation bands are inclined subparallel to the c-axis, unlike the natural deformation bands, many of which are inclined at very low angles to the basal plane (Fig. 3). CARTER *et al.* (1964) and CHRISTIE *et al.* (1964) clarified that the experimentally produced bands subparallel to the c-axis resulted from translation gilding parallel to {0001} and kinking of the glide planes, and they interpreted that the experimentally produced bands subparallel to {0001} originated by translation gliding parallel to the prism planes and kinking of the glide planes. The experimentally produced bands tend to be preferably oriented at an angle ca. 45° to the compression axis, like the case of the natural bands. For the experimentally produced bands subparallel to the c-axis "the sense of rotation of the c-axis from the host to the band is most commonly toward σ_1" (compression axis), and "bands inclined at 70°-90° to the c-axis show some apparent consistency in that the c-axes in the bands are generally rotated away from σ_1' ...." (CARTER*et al.*, 1964, p. 713). This character of the lattice rotation in the bands is quite inconsistent with that of the natural bands mentioned in the preceding paragraph. Such a sense of the lattice rotation from the host to the band that is for the natural deformation bands was also equally observed for the experimentally produced deformation bands in metalic crystals (e.g. CHEN and MATHEWSON, 1951; NISHIMURA and TAKAMURA, 1952). According to Fig. 12-c of CARTER *et al.* 1964, for many of the deformation bands inclined at low angles to the basal plane the angle CL∧L⊥ is larger than the angle Ch∧L⊥, unlike the case of the natural deformation bands. Therefore, it is doubtful if the experimentally produced deformation bands are essentially the same as the natural deformation bands.

Strictly speaking, the band width is variable not only between individual grains but also even within a single grain. For statistical analysis of the variation in the band width in each specimen, the measurement was made on sixty bands in twenty grains, three bands from each grain which contain two bands in the marginal part and one band in the central part of the grain. The results are shown in Fig. 12.

The variation in the band width within the individual specimen is fairly large, and the maximum range of variation is about 0.04 mm in the specimen IV. A single marked maximum is found in each of the histograms (Fig. 12). Fig. 12-a shows that many of the bands in the specimen II is less than 0.01 mm in width and that the maximum width is ca. 0.02 mm. In Fig. 12-b for the specimen III there is a peak (the most frequent width) at between 0.005 mm and 0.02 mm and the maximum width is ca.

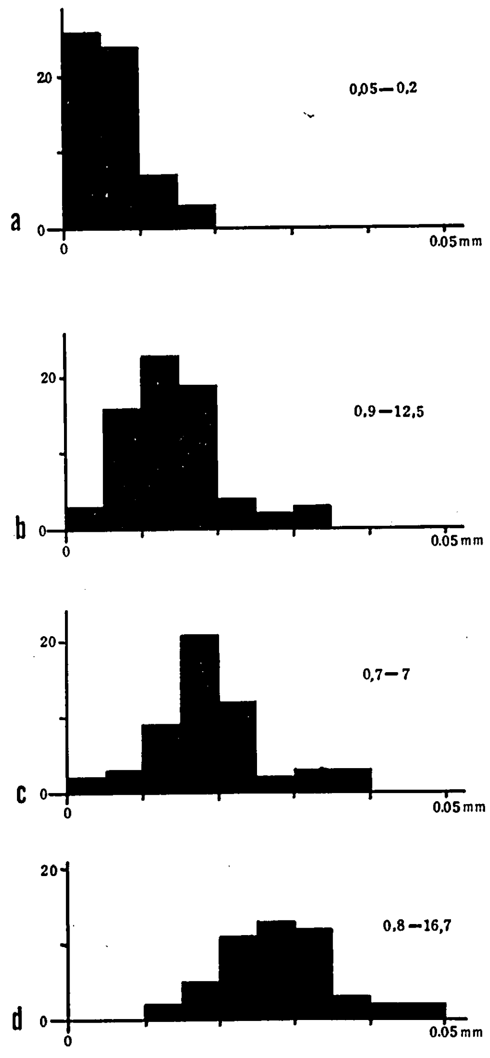

FIG. 12. Histogram showing the variation in the width of deformation bands in the specimens I (c), II (a), III (b) and IV (d). Numbers in the upper-right corner of the individual diagrams show the size of grains containing the deformation bands in mm. Frequency is given by number of deformation bands.

0.035 mm. In Fig. 12-c for the specimen I there is a peak at between 0.01 mm and 0.0 25 mm and the maximum width is ca. 0.04 mm. In Fig. 12-d for the specimen IV there is a peak at between 0.02 mm and 0.035 mm and the maximum width is ca. 0.05 mm. Both the maximum frequent width and the maximum width of the bands are different between the specimens I to IV. The former is proportional to the latter, that is, the former increases with increase in the latter. Therefore, it can be concluded that, though the width of deformation bands in quartz is not constant but considerably variable, within a restricted domain (each specimen) the bands with a specific width tend to develop predominantly. Now, it comes into question what causes are related to the difference in the maximum frequent width between the specimens I to IV.

Grain size of quartz containing the deformation bands in each of the specimens I to IV is shown in Fig. 12. In the specimen described by the author *et al.* (1965) the bands less than 0.01 mm in width are commonly found in quartz grains larger than 3 mm in size. The band width does not appear to be always dependent upon the grain size.

According to the knowledge of creep deformation of metalic crystals, both the width of deformation band (kink band) and the subgrain size are dependent upon the rate and temperature of deformation, that is, both the former and the latter increase with increase in temperature and decrease in strain rate (cf., HIRSH, 1956; DORN, 1961). Analogous relationship of the effect of strain rate and temperature on the band width and subgrain may also be equally valid for the deformation bands in quartz.

According to the microscopic observation, generally, many of band-boundaries are displayed by a combination of sharp but continuous change of extinction position and discontinuous change of it, but some other band-boundaries only by discontinuous change of extinction position, showing the development of subgrains which occur in bands. The discontinuous band-boundaries would have been produced by polygonization in the continuous band-doundaries. In each of the specimens I to IV, the width of the banded subgrains is essentially the same as that of the deformation bands with continuous band-boundaries, whose result is shown in Fig. 12. Such process of crystal fragmentation of quartz (deformation bands → polygonization of band-boundaries → subgrains) appears to be compared with that in creep deformation of metalic crystals, in which the subgrain size decreases with increase in stress, increase in strain rate or decrease in temperature, described by McLEAN (1951 and 1952), GERVAIS *et al.* (1953), KELLY *et al.* (1953) and others.

The following two types of syntectonic recrystallization of quartz have been distinguished by the author *et al.* (1966): 1) The shapes of recrystallized new grains developed in the host grains are strongly elongated parallel to the direction of mass elongation of the system concerned but the reorientation of the c-axes (lattice) of those grains are scarcely induced during the deformation, that is, the formation of preferred dimensional orientation and little lattice reorientation, (here termed Type II of syntectonic recrystallization of quartz). 2), The formation of preferred dimensional and lattice orientation (Type III). Those two types of syntectonic recrystallization of quartz must be distinguished from the present type of that which is shown only by polygonization of bending lattice (e.g. band-boundaries) and from what is characterized by the formation of recrystallized new grains which do not show the formation of preferred dimensional and lattice orientation (Carter, *et al.*, 1964), (here termed Type I). The Type II appears to be an intermediate type between the Type I and Type III. According to the microscopic observations of siliceous metamorphic tectonites, it can be pointed out that those three types of syntectonic recrystallization of quartz take commonly place under the physical conditions in which metamorphism can occur. The Type I, Type II and Type III of syntectonic recrystallization of quartz would correspond to respective types of deformation of quartz occurring under metamorphic condition. It may be pointed out that diffusion processes become progressively dominant in deformation of quartz, passing from the Type I, through the Type II, to the Type III. Increase in temperature may activate diffusion of atoms and decrease in it may weaken that. Temperature appears to be important as the controlling factor which governs the deformation mechanism of quartz. The driving force for recrystallization of deforming crystals is generally also considered to be the internal strain energy and the grainboundary energy of them. The grain size of quartz would also be very important as the controlling factor which governs the deformation mechanism of quartz (HARA *et al.*, 1966). Deformation bands do not appear to be formed in quartz grains giving rise to the syntectonic recrystallization of Types II and III.

Under the physical condition in which the Type I of syntectonic recrystallization of quartz can occur, plastic deformation of quartz appears to be taking commonly place in the following three types: 1) Quartz grains are deformed in such a manner as only the undulatory extinction is formed in them. 2) The deformation bands and undulatory extinction are formed in quartz grains. And 3) the formation of the deformation lamellae and undulatory extinction. It is important to clarify the genetic relationships (transition conditions) between those three types of plastic deformation of quartz and between the Type I, Type II and Type III of syntectonic recrystallization of quartz. The solution of the above-described problems requires further experimental study of deformation of quartz under various physical conditions.

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