are within 2°–4° of the measured values, consistent with the errors in measuring the orientations of the planes.

It was noted above that the slip direction in an ideal kink band must lie in the slip plane perpendicular to the axis of external rotation, which is the intersection of the slip plane and the kink boundary. Hence if the slip plane in a band is known, the slip direction is also determined. It is evident from our study of the orientation of the deformation bands parallel to the $c$-axis that their orientations are quite variable and that they are not systematically parallel to a single prismatic form. The following generalizations are based on measurements of the orientation of bands in a large number of crystals of orientations $0^+$, $\perp r$, $\perp z$.

In crystals of the $0^+$ orientation, in which the maximum resolved shear stress in the base is parallel to an $a$-axis, the external-rotation axes in the relatively few bands found were invariably in the basal plane, perpendicular to the direction of maximum resolved shear stress. This indicates that slip was parallel to the $a$-axis and is consistent with the results obtained from the polished crystals.

In crystals compressed perpendicular to the rhombohedra $r$ and $z$, however, there is considerable variation in the orientation of the band boundaries, even within a single specimen. The orientations of the bands and the external-rotation axes in the bands for a typical specimen of this group, C-143, are shown in figure 5; this specimen is shown in plate 4, *B*, of the preceding paper. The specimen was compressed perpendicular to $z$ at a confining pressure of 22 kb., and the temperature in the center of the cylinder was 750° C.[7] Figure 5, *a*, shows the orientation of a single-band boundary, the $c$-axes outside and inside the band ($c_1$ and $c_2$, respectively) and the external-rotation axis deduced from the orientations of the $c$-axes. The external-rotation axis lies in the base perpendicular to one of the $a$-axes, indicating that slip was parallel to the $a$-axis close to the pole of the band. In figure 5, *b*, however, the orientations of band boundaries and external-rotation axes are shown for several other bands in the specimen. The poles of the bands spread continuously through approximately 45° in a zone close to the base, and there is a similar variation in the orientation of the external-rotation axes. These variations are characteristic of crystals of this group ($\perp r$, $\perp z$) deformed at 750° C. and lower temperatures. The variations are real, since the boundaries can be measured within 2°–3°. It may be noted that the axes of external rotation lie in the

TABLE 2

ANGULAR RELATIONS OF CRYSTAL SURFACES IN BANDS MEASURED AND CALCULATED ASSUMING BASAL SLIP

| Crystal | Locality | $\theta_1$° | $\theta_2$° | External Rotation° | $\beta_1$° | $\beta_2$° | |
|---|---|---|---|---|---|---|---|
| | | | | | | Measured | Calculated |
| 266 | A | 89 | 108 | 19 | 44 | 53 | 54 |
| 116 | A | 84 | 100 | 16 | 37 | 47 | 44 |
| | B | 87 | 101 | 14 | 37 | 40 | 43 |
| 12 | A | 89 | 104 | 15 | 41 | 46 | 49 |
| | B | 87 | 102 | 15 | 42 | 46 | 50 |
| 146 | A | 87 | 98 | 11 | 42 | 45 | 48 |

[7] *Note added in proof.*—Since this was written, further work has revealed evidence of systematic error in these temperatures as discussed in n. 4, p. 694, of the preceding paper.

basal plane, supporting the conclusion that the base is the active slip plane.

The continuous variation in the orientations of band boundaries and rotation axes suggests a similar continuous variation of the slip direction in (0001). But since the deduced slip directions vary between the two *a*-axes with high (and equal) resolved shear-stress coefficients, we prefer the explanation that they are resultant slip directions due to simultaneous slip parallel to these two *a*-axes. Simultaneous operation of two *a*-axis slip directions also appeared likely from the study of polished specimens of these orientations.

There is some evidence that the orientation of the bands varies systematically with temperature in the crystals deformed in such a way as to favor slip parallel to two *a*-axes. In a crystal deformed at 900° C. (C-116) the external-rotation axes are all parallel to the *a*-axis with zero resolved shear stress, indicating that the slip was apparently parallel to $a^*$, the direction with highest shear stress in the base.[8] In the crystals deformed at 750° C. (C-143, 150, 334, 259), which contain the best-developed bands, the majority of the bands are oriented so that their poles are parallel to $a^*$, but several in each specimen are oriented so that their poles are subparallel to the *a*-axes. The latter are all in the cooler end portions of the cylinders (500°–600° C.), but some of the bands in these parts of the crystals are also oriented with poles parallel to $a^*$; the bands which originate against the carbide end pieces are invariably of this last orientation. Similar variations of orientation were observed in crystals deformed at 500° C. (C-144, 146), the bands indicating *a*-axis slip again being near the ends of the crystals. The few bands in crystals deformed at 300° and 400° C. (C-125, 148) indicate slip parallel to the *a*-axis in the central parts of the cylinders, but some bands which abut against the carbide end pieces show an apparent slip parallel to $a^*$. Though the data are not conclusive, they suggest that in the cooler parts of the crystals only one of the two *a*-axes with high shear-stress coefficients operates. The exceptions to this may be due to constraints imposed on the ends of the crystals by the carbide end pieces.

Since deformation bands are very rare in crystals oriented favorably for slip parallel to a single *a*-axis, it is possible that the formation of the bands is dependent on the operation of two *a*-axes as slip directions in crystals deformed so that both have equal shear-stress coefficients.

There are consistent departures in the *c*-axis bands in our samples from the ideal symmetrical kink boundary. On the basis of measurements on fifty-four bands in ten single-crystal samples, the angle $\theta_1$, measured as indicated in figure 4, *a*, ranges from 79° to 99°, with an average of 88° (to the nearest degree); $\theta_2$ ranges from 90° to 113°, with an average of 102°. The external rotations across the band boundaries are between 5° and 30°, the average being 14°. The angles between the band boundaries and the axis of compression ($\phi$) vary from 32° to 59°, with an average of 46°, consistent with the relationships observed by Carter *et al.* (1964) in polycrystalline samples. There appears to be no correlation between the angles $\theta_1$ or $\theta_2$ and the external rotations: that is, the asymmetry of the bands does not change consistently with the amount of deformation in the bands. Nor, in general, are there consistent relationships between the angle $\phi$ and either $\theta_1$, $\theta_2$, or the external rotations.

The origin of this asymmetry will be discussed after consideration of the dislocation model of kink bands.

#### DISLOCATION MODEL OF KINK BANDS

The first simple dislocation model of a kink band was proposed by Hess and Barrett (1949), who suggested that, with progressive deformation, edge dislocations accumulate in the slip planes at bend or kink boundaries, causing rotation of the material in the band with respect to the rest of the crystal. The dislocations at each boundary are of opposite sign (fig. 6, *a*). By the process of polygonization (Cahn, 1951) the disloca-

[8] Bailey, Bell, and Peng (1958) reported external rotation about an *a*-axis in naturally deformed quartz.