DEFORMATION OF EXPERIMENTALLY SHOCKED BIOTITE*

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ABSTRACT. The results from a series of shock experiments (10-40 kb) on single
crystal lepidomelane (Bancroft, Ontario), imbedded in an impedance matching medium,
NaI, show that kinking occurs at pressures of as low as 9 kb. The intensity of kinking
is related to peak pressure and shock pulse duration (0.1-0.3 μsec). Kinking is produced
by shocks propagating along [hk0] and not along [001].

The shock-induced kinks have a wider range of their angle of external rotation
(19-121°) than their static counterparts (40-60°). The ratio of the kink angles, e and δ,
scatters widely, indicating that kinking which is shock-induced is highly asymmetrical.
Gliding lines and angles of external rotation are not controlled by crystal structure. A
marked decrease of 2V from 24 to 7° with increasing pressure is observed. Laue trans-
mition patterns show that permanent angular rotations as great as 4.4° are induced by
shock pressures of 37.5 kb. In individual samples the increase in permanent angular
rotations and decrease in 2V can be closely correlated.

INTRODUCTION

Kinking, although not an unusual feature in silicates and other rock
forming minerals, is especially prominent in micas; this includes both
biotite and muscovite. Kink bands in micas were reported by Becke as
early as 1882 and in kyanite by MÜGGE (1898). MÜGGE suggested that kinks
result from a combination of translation gliding in a plane T, parallel to
the glide direction t, and an external rotation around a rotation axis f of
discrete volumes of the crystal (see fig. 1).

Under the microscope, kinks appear as sharply defined bands. In
micas they usually appear as lens-shaped structures with very distinct,
but usually curved, borders. Often large numbers of kink bands are ob-
erved in an individual grain, typically giving rise to a chevron-type
structure.

Kinked micas have been reported in various tectonically deformed
rocks (see, for example, Becke, 1882; PHILLIPS, 1939; and TURNER, 1964).
GRIGGS, TURNER, and HEARD (1960) produced them in mica within a series
of cylindrical granite specimens by static deformation (compression) at
500°C under a hydrostatic pressure of 5 kb. The kinkbands formed
preferentially in biotite crystals oriented with the {001} cleavage inclined
at less than 45° to the axis of compression. This dependence on the direc-
tion of maximum principal stress was confirmed in TURNER's study of a
tectonically deformed gneiss and by BORG and HANDEL (1966) in a detailed
experimental study. BORG and HANDEL also noted crystallographic control
of kink axes in biotite single crystals and biotite-bearing rocks deformed
at 5 kb and 500°C.

Recently, kinked biotites have also been described in rocks associated
with known and/or suspected meteorite impact craters (STOFLE, 1967;

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1213
Fig. 1. Development of kink bands according to Mügge (1898) (after Borg and Handin, 1966). A, undistorted crystal; B, gliding and bending; C, formation of first kink; D, complex kinking.

Chao, 1968; Bunch, 1968) and nuclear explosions (Short, 1964; Cummings, 1965, 1968). Cummings (1968) and Hörz (1969) placed the approximate minimum shock pressure for their formation at about 10 kb on the basis of shock attenuation calculations.

This paper presents a preliminary report of a laboratory study of the effect of shock waves on single crystals of biotite. The effects of shock waves on biotite were investigated using petrographic and X-ray techniques, and the stress levels required to induce various levels of shock damage were quantitatively determined.

SHOCK LOADING EXPERIMENTS

Our specimen material was a lepidomelane from Bancroft, Ontario¹ (see table 1). Targets approximately 1 cm square and varying in thickness from 0.1 to 0.2 cm were cut from a large single crystal in three orthogonal directions: \{001\} and nominally \{hk0\} and \{hk0\} + 90°.

Table 1

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>39.00</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>10.76</td>
</tr>
<tr>
<td>TiO₂</td>
<td>2.22</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>17.82</td>
</tr>
<tr>
<td>FeO</td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>13.91</td>
</tr>
<tr>
<td>MnO</td>
<td>0.89</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.53</td>
</tr>
<tr>
<td>K₂O</td>
<td>8.74</td>
</tr>
<tr>
<td>ZnO</td>
<td>0.13</td>
</tr>
<tr>
<td>CaO</td>
<td>trace</td>
</tr>
<tr>
<td>H₂O</td>
<td>6.00**</td>
</tr>
</tbody>
</table>

| Total     | 100.00            |

* A. Albee (private commun.)
** inferred value

¹ Obtained through the courtesy of Dr. E. C. T. Chao of the U. S. Geological Survey.
Deformation of experimentally shocked biotite

The targets were imbedded in an impedance matching medium which in all cases was polycrystalline NaI with a density of 3.5 g/cm³. The shock impedance of the biotite, whose Hugoniot is unknown, was approximated using the ultrasonic data for various micas of Alexandrov and Ryzhova (1961). We chose NaI as an impedance matching medium on the basis of the Hugoniot data of Christian (reported in van Thiel, 1966). This material can be conveniently molded in a vacuum hot press so as to form a cylindrical pellet with the one surface of the sample exposed. The geometry employed in the impact experiments is indicated in figure 2. A polycrystalline pellet of an alkali halide is expected to have relatively low tensile strength (Linde and Doran, 1966). Upon reflection of the shock at the rear pellet surface, incipient spalling of the NaI is expected, and most of the momentum of the shock wave is carried off by the resultant spray of NaI material. As a result of the momentum trapping in the NaI, the biotite samples acquire minimal net particle velocity and thus are only slightly damaged by secondary impacts in the recovery box.

A 20 mm smoothbore powder gun was used to accelerate the projectile in the present experiments. The flyer plate materials embedded in the Lexan projectile head were Lexan (no flyer plate), brass (McQueen and Marsh, 1960), or Fansteel 77 (Jones, Isbell, and Maiden, 1966). The projectile velocity was measured prior to impact with the light detector system indicated in figure 2. Although the velocities in the present experiments were measured to only ±2 percent, this system is capable of precision of better than 1 percent. Using Christian’s data for NaI and appropriate equations of state for Lexan, brass and Fansteel 77, the shock state in the NaI was obtained using a graphical impedance match solution (McQueen and Marsh, 1960).

Since no Hugoniot data for biotite are available, the quoted pressures are those in the NaI pellet. When Hugoniot data for biotite become

![Figure 2](image-url)

Fig. 2. Impact geometry for present experiments; prior to impact projectile velocity is obtained with laser-photodiode system.
available, the pressures quoted here will have to be revised. We believe the quoted pressures are within ±20 percent of those actually produced in biotite. Fortunately, most of the following results are not sensitive to specific pressure levels.

The shock pressure range available for these experiments was 10 to 40 kb. The lower limit being controlled by the increased tendency of the projectile to tilt at low velocities (≈ 200 m/sec), the upper limit corresponds to the maximum projectile velocity obtainable with this powder gun (≈ 600 m/sec).

The shocked biotite samples were recovered by simply dissolving the NaI in water. The grain size of the recovery products ranged from several millimeters to 1 micron. For the petrographic studies, powder mounts which permitted observation parallel (type A) and perpendicular (type B) to the biotite's {001} plane were employed. Type A was made by simply applying slight pressure on the cover glass to ensure that the flakes rested with their cleavage surface on the microscope slide. Type B was produced by slicing a complete mount of type A into 1 to 2 mm wide strips. The individual strips were rotated 90°, fastened to a new glass slide, and lapped down to the appropriate thickness. Type A powder mounts (pl. 3) were used to measure the kinkband orientation with respect to the biotite indicatrix, and type B powder mounts (pl. 2-B) were used to measure the geometrical parameters of the kinks. The petrographic data were obtained using standard universal stage techniques and stereonet plots.

FORMATION OF KINK BANDS

The present data relating impact parameters with the occurrence of kink bands are summarized in table 2 and figure 3. As expected, the crystallographic orientation of the samples strongly controlled the formation of kinks. Virtually no kinks were observed in specimens in which the shock propagated perpendicular to {001}. In a few cases where these were

<table>
<thead>
<tr>
<th>Shot no.</th>
<th>Projectile material</th>
<th>Impact velocity (m/sec)</th>
<th>Peak pressure in NaI (kb)</th>
<th>Pressure duration (μsec)</th>
<th>Plane of shock</th>
</tr>
</thead>
<tbody>
<tr>
<td>B3</td>
<td>Lexan*</td>
<td>572</td>
<td>13</td>
<td>0.31</td>
<td>(001)</td>
</tr>
<tr>
<td>B4</td>
<td>Fansteel 77**</td>
<td>499</td>
<td>37.5</td>
<td>0.06</td>
<td>(001)</td>
</tr>
<tr>
<td>B7</td>
<td>Brass***</td>
<td>563</td>
<td>29.0</td>
<td>0.06</td>
<td>(hkO)</td>
</tr>
<tr>
<td>B13</td>
<td>Brass</td>
<td>420</td>
<td>27.0</td>
<td>0.20</td>
<td>(hkO)</td>
</tr>
<tr>
<td>B14</td>
<td>Brass</td>
<td>398</td>
<td>24.0</td>
<td>0.32</td>
<td>(001)</td>
</tr>
<tr>
<td>B15</td>
<td>Brass</td>
<td>385</td>
<td>23.0</td>
<td>0.08</td>
<td>(hkO) + 90°</td>
</tr>
<tr>
<td>B16</td>
<td>Brass</td>
<td>510</td>
<td>34.0</td>
<td>0.07</td>
<td>(hkO) + 90°</td>
</tr>
<tr>
<td>B17</td>
<td>Lexan</td>
<td>370</td>
<td>9.0</td>
<td>0.31</td>
<td>(hkO)</td>
</tr>
<tr>
<td>B18</td>
<td>Lexan</td>
<td>374</td>
<td>9.0</td>
<td>0.31</td>
<td>(hkO)</td>
</tr>
</tbody>
</table>

* A polycarbonate plastic, General Electric Co.
** 99% W, 6% Ni, 4% Cu
*** 61.5% Cu, 35.2% Zn, 3.2% Pb
observed they were exclusively confined to the periphery of the grains, and therefore their formation was attributed to secondary impacts (on the walls of the recovery box).

At a pressure of 9 kb, kinking was easily detectable for impact directions \( \{hk0\} \) and \( \{hk0\} + 90^\circ \). With increasing pressure, the frequency of kinking increases. No appreciable difference in kink band formation between \( \{hk0\} \) and \( \{hk0\} + 90^\circ \) was observed. A dependence of kink formation on the pressure duration is indicated in figure 3.

GEOMETRY OF KINK BANDS

Examples of recovery products (pl. 1-A and B, pl. 2-A) display a kink band structure and superficially resemble those found in tectonically deformed rocks. Using type B powder mounts (pl. 2-B) successive alignment of the (001) planes in adjacent bands with the microscope tube and rotation of the microscope stage allowed precise measurement of the angular parameters of the kink bands. Following the definition of Starkey, we measured the angles between \( \{001\} \) planes and kink band boundary in “host” and kinked areas. We define \( \varepsilon \) as the smaller of the two angles \( \varepsilon \) and \( \delta \), hence the data in figure 4 lie asymmetric about the line, \( \varepsilon = \delta \). A considerable spread in absolute values as well as ratios of \( \varepsilon / \delta \) is obvious. Peak pressure and pressure duration do not seem to affect this spread (fig. 4).

Borg and Handin (1966) report values of \( \delta \) and \( \varepsilon \) in statically deformed single crystals in the range of 51° to 84° (fig. 4). They also report
Typical kinking in recovered biotite (23 kb, impact direction (hk0) + 90°). A. normal plane light, B. crossed nicols.
A. Complex kinking (39 kb, impact direction (hk0)).

B. Kinking as seen parallel to \{001\}. Note the high angle of $\alpha(=90^\circ)$. Kinking at left is highly asymmetric.
Fig. 4. Values for $\epsilon$ and $\delta$ in kinks from shocked biotite at various pressures.

Fig. 5. Statistical distribution of $\omega$ (shot B13, 27 kb; 124 measurements).
that $\delta$ and $\epsilon$ do not deviate by more than about $5^\circ$ from each other, that is, the kinking generated statically is nearly symmetric about the kink boundary. Turner (1964) obtained similar results in a mica schist. In the present experiments, $\epsilon$ and $\delta$ differed from each other by up to $32^\circ$.

Since $\epsilon$ and $\delta$ vary considerably in their absolute value, the angle of external rotation $\omega$ also varies widely, that is, $\epsilon + \delta + \omega = 180^\circ$. A statistical plot for shot B13 (fig. 5) shows that the values of $\omega$ have a wider variation than the range of Borg and Handin's data. The most frequent value of $\omega$ is in the range $40$ to $60^\circ$. About 15 percent of our kinks have rotation angles of more than $90^\circ$ (fig. 5). This large a spread ($19$-$120^\circ$) has not been reported previously in any tectonically deformed rocks.

As mentioned above, kinking in biotite is thought to be represented by gliding (in $\{001\}$) combined with external rotation (fig. 1). Borg and Handin report a translation line along $[100]$, the corresponding rotation axis being $[010]$. The possibility of kinking along other axes was left open by Borg and Handin. If there are other possible translation lines in the $\{001\}$ plane, the corresponding rotation axes will be of the type $[hk0]$.

We investigated this possibility with the present shock-loaded specimen material since a large number of grains display very regular kinks (pl. 2-B). Viewing these grains along $\approx [001]$ (type A mount), a series of

PLATE 3

Kink bands as viewed along $\epsilon_{\omega}$ (001) (shot B13, 27 kb).
sharp stripes are easily observed (pl. 3). An idealized situation is drawn in figure 6.

Since the rotation axes are confined to the \{001\} plane, it is only necessary to measure the trend of the kink boundaries in relation to the indicatrix axes, \( n_x \) and \( n_z \). Therefore each suitable grain was oriented under the microscope (U-stage) with its optical plane parallel to the north-south crosshair. The angle between the kink band boundary and the crosshair then yields \[hl0\] for the rotation axis.

Three examples of such measurements are plotted in figure 6 in a simplified stereoplot. All grains were normalized by aligning their indicatrix axes. It appears that in the shock loaded biotite there is no crystallographic control of glide direction or axis of external rotation. We infer from these experiments, and from the earlier static observations, that the axis of rotation must be perpendicular to the maximum principal stress direction. Consequently, the translation direction is approximately parallel to the maximum principal stress.

In order to verify this, a granite shock loaded to \( \sim 35 \) kb in a previous cratering experiment (Hörz, 1968) was thin sectioned parallel to the impact direction. Only biotite grains oriented such that their optical plane was within 85\(^\circ\) to the normal to the thin section were measured. The orientation of the indicatrix axes, \( n_x \), \( n_y \), and \( n_z \), was then determined. Since the kink bands were not as well developed and did not dis-
play the sharp stripes of the single crystal recovery products (as viewed along [001]), Cummings's (1968) technique was employed to measure their orientation: the azimuth of the longer axis of the lens-shaped kinks was measured. (The actual boundaries, although not straight, were assumed to correspond to the rotation axes. Since the kink boundaries intersect at angles of typically less than 20°, the measured orientations of the rotation axes are probably accurate to ± 10°.)

The orientation of \( n_x \) and \( n_y \) in the biotite in this granite (fig. 7) was found to be almost random. (A slight preferred orientation of the biotite was noted; this, however, is not relevant to the present discussion.) Despite the random orientation of \( n_x \) and \( n_y \) with respect to the impact direction, the larger axes of the kink bands cluster at 90° to the maximum principal stress direction. This not only verifies Cummings' observations on the granite of the Hardhat event but also demonstrates that the rotation axis for shock-induced kink bands in micas lies at \( \approx 90^\circ \) to the principal stress direction, independent of the crystallographic orientation.

In tectonically deformed gneiss (see Turner, 1964), micas are usually oriented with their c-axes perpendicular to the S (schistosity) planes of the rock. The azimuth of \( n_x \) and \( n_z \) is presumably random within the S-plane. If it is possible to use the orientation of kink bands to reconstruct the direction of principal stress in gneisses, it seems to follow that under

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**Fig. 7.** Orientations of \( n_x \), \( n_y \), and \( n_z \) and corresponding rotation axes in biotite from a shocked granite. Arrow indicates shock propagation direction. Histogram indicates distribution of kink axes relative to impact direction.
tectonic (as well as dynamic) loading, translation lines are probably not crystallographically controlled in an obvious way. The data for shock loaded granite shown in figure 7 support this hypothesis, as the kink band axes are oriented perpendicular to the direction of principal stresses. Again no obvious crystallographic control of kink axes was detected.

2V MEASUREMENTS

In the initial higher shock pressure experiments a marked decrease in the angle between the optic axes (2V) of this biaxial crystal was noted; this led to a more detailed study. We found that the decrease of 2V is more pronounced for impacts along \( \approx [001] \) (fig. 8). Unshocked material displayed a 2V of 24° (fig. 8). The lowest 2V observed in the shocked lepidolite was 7° for material shocked to 37.5 kb. Although the material from each shot displayed a large variation in the values of 2V, a clear decrease of 2V with increasing pressure is observed. The accuracy of each measurement is \( \pm 2° \). No change in refractive indices, corresponding to the change in 2V, could be observed.

Cummings (1965) reports anomalous interference figures in the biotite of the granodiorite of the Hardhat event. This feature was found only in sample B13. At higher pressures but shorter pressure durations anomalous interference was not observed. It may be that the decrease in 2V is due to rotation of the silicate sheet structure about the c-axis, thus corresponding to a slight change in the stacking sequence. According to

![Graph](image)

**Fig. 8.** 2V versus pressure. Uncertainty bands indicate 80 percent confidence interval (20 measurements per shot).
Laue transmission photographs of shocked biotite. A. Raw material. B. 9 kb, plane of shock is (hk0). C. 37 kb, plane of shock is (001).
Bloss, Gibbs, and Cummings (1963) the formation of anomalous interference figures is due to an irregular stacking order of individual mica sheets. Bloss also reports that orientation of the optic plane may vary within a laminar of mica flakes. Since the change in 2V in the present experiment can not be attributed to changes in refractive indices or to any chemical reactions (for example, selective volatilization), we think that irregular stacking is responsible for the drastic 2V changes.

**X-ray data**

Debye-Scherrer powder patterns of various shocked samples, when compared to the unshocked standard, revealed no abnormalities; the pressures achieved are presumably not high enough to affect the biotite structure on a sub-unit cell scale. This is not surprising, since in naturally shocked rocks the sheet silicates show remarkable stability even at shock pressures exceeding 300 kb. This is evidenced by the coexistence of micas and shock induced glasses of tectosilicates (quartz and feldspar) in impacted rocks.

A series of several mica flakes from each of the impact experiments was examined by the Laue transmission method, using Mo-radiation (pl. 4. The samples were aligned so that [001] was parallel to the beam.

As can be seen in plate 4, the degree of asterism in the Laue patterns correlates closely to the shock pressure levels and hence presumably to the degree of internal strain present in the samples. In order to obtain a quantitative measure of the degree of permanent strain, we measured the major axis lengths of the asterated Laue reflections (Cullity, 1967). After correction for the width of the reflection in the unshocked control

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**Fig. 9. Angular rotation versus shock pressure.**
sample, the strain angle (ε), as measured radially outward from the axis of the X-ray beam, was obtained.

The results (fig. 9), as in the case of the 2V data, show considerable scatter when correlated with shock pressure; however, a clear dependence on pressure level is obvious.

In order to correlate 2V and ε more closely, a series of samples were selected, and both parameters were directly measured. As can be seen in figure 10, they are strongly correlated. We interpret the X-ray asterism as arising from small lattice areas which are tilted and (probably) rotated, thus forming a mosaic-type structure. The X-ray unit cell is unaffected, and when the material is ground up for analysis in the Debye-Scherrer geometry, it yields a normal pattern.

**DISCUSSION**

The kink bands produced in these experiments appear at pressures as low as 9 kb. Although we have not established the lower pressure limit for their formation, Cummings (1968) and Hötz (1969) showed that in initially undeformed granite they fade out at pressures of ≈ 10 kb. A gradual transition to normal features of tectonic origin (≈ 1 kb) apparently does not occur. This indicates that kink band formation under shock is due largely to the combination of peak pressures and the large accompanying dynamic strain. Longitudinal strains up to 20 percent were detected in some of our recovered samples. This idea is supported by the results from shot B13, for which the pressure duration was the longest (above 15 kb and for [hk0] impacts) and the flow was also the
least planar (due to finite (13 mm) diameter of the projectile) of any of the shots. The resulting B13 specimen material also had the highest frequency of kinks of any of the specimens. Apparently, even in nuclear explosions (see Cummings) the pressure duration is not sufficient to produce kink bands at pressures lower than \( \approx 10 \, \text{kb} \). Pressure durations in large natural impact events are of the same orders of magnitude as in the nuclear explosions.

The angular relations in the kink bands produced in these experiments indicate that in practice it may be possible to differentiate between a static or dynamic (shock wave) origin. The high stress and strain rates induced by passage of a shock wave are probably responsible for the observed asymmetry in kinking as well as the large values of external rotation angle (neither of which are reported from tectonically deformed rocks). However, caution has to be expressed so as not to overemphasize this result, as there are few reported data available giving kinking geometry parameters in tectonically deformed or naturally shocked micas. It should also be noted that our experiments employed single crystals that were not confined in the same way as micas in a dense rock. More work should be done in this direction.

The present measurements of kink rotation axes, and therefore gliding lines, reveal that these are probably not crystallographically controlled. The external rotation axis is perpendicular to the maximum principal stress direction.

In the static deformation experiments of Patterson and Weiss (1966) in which phyllite was compressed parallel to the foliation, macroscopic kink bands were produced. These experiments demonstrated that the rotation axes lie in the foliation plane and are predominantly perpendicular to the maximum principal stress. We think that the relatively weak bonds between individual mica-sheets result in a similar mechanical behavior of mica. Patterson and Weiss also report that the scatter in \( \omega \) is nearly independent of experimental conditions. Our experiments indicate a similar result.

We also conclude that, because of the apparent lack of crystallographic control, Starkey's (1968) model of kink band formation does not account for kinking in micas deformed by shock.

ACKNOWLEDGMENTS

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