(*20*) and the Pethei Formation (*21*)—the 2-billion-year-old Pethei stromatolites are of particular interest, because Hoffman (*21*) believes that the different forms grew in a great variety of environments extending from the shore to shelf-edge reefs. To consider a modern equivalent we would have to imagine the entire Bahama Banks covered with stromatolites.

Blue-green algae today inhabit an enormous range of environments (*22*). It is their remarkable ecologic tolerance that has enabled stromatolites to persist to the present time. The compelling evidence for restriction of stromatolites by animals is especially important in that few, if any, similar relationships have been well documented in the fossil record. In contrast to the many well-known examples of ecologic displacement of groups by better-adapted competitors, the stromatolite example is one of suppression of a group by interacting but noncompetitive organisms, so that the fossil record of that group is limited ecologically and areally to the narrow extremes of its broad adaptive range.

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## Deformation Twins in Hornblende

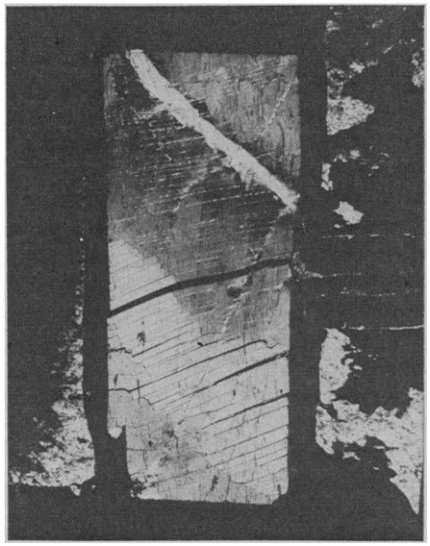
Abstract. *Hornblende deformation twins with twin planes parallel to* ($\bar{1}01$) *are produced experimentally in single crystals by compression parallel to the* c *axis. Twinning occurs at confining pressures from 5 to 15 kilobars and temperatures from 400° to 600°C (strain rate,* $10^{-5}$ *per second).*

Lamellar features approximately parallel to (100) and ($\bar{1}01$) are commonly reported for clinoamphiboles. Recently, numerous amphibole minerals containing lamellae were examined by x-ray single crystal, optical, and microprobe techniques (*1*, *2*). These studies clarify the relations between the optical direc-

Table 1. Pressure-temperature conditions for twinning in hornblende. Test conducted at a strain rate of $10^{-5}$ per second.

| Test | Confining pressure (kb) | Temperature (°C) | Longitudinal strain (%) | Twins (No.) | Development* |
|---|---|---|---|---|---|
| A1-63 | 5 | 400 | 9.5 | 25 | 2 |
| A1-72 | 5 | 600 | 10.0 | 10 | 3 |
| A1-54 | 10 | 400 | 10.5 | 18 | 2 |
| A1-55 | 10 | 600 | 13.0 | 10 | 3 |
| A1-58 | 15 | 400 | 12.2 | 100 | 1 |
| A1-59 | 15 | 600 | 10.0 | 100 | 1 |
| A1-78 | 20 | 400 | 10.9 | 15 | 2 |
| A1-61 | 20 | 400 | 11.3 | 12 | 2 |
| A1-73 | 20 | 600 | 9.0 | 14 | 3 |

* 1, excellent; 2, fair; 3, poor.



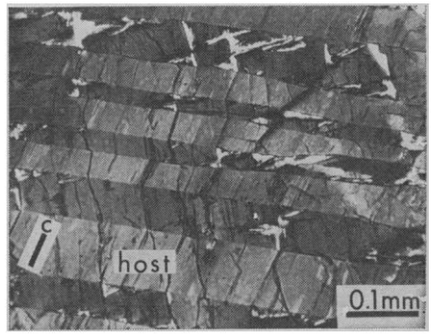



Fig. 1 (left). The ($\bar{1}01$) twin lamellae developed in deformed cylinder of hornblende (A1-58T). Crystallographic *c* axis approximately parallel to length of cylinder, which is also direction of maximum compression. Diagonal, light-colored area is ductile zone. Note pronounced parting along ($\bar{1}01$) planes. Confining pressure, 15 kb; temperature, 400°C. Length of cylinder is 7 mm. Fig. 2 (right). Magnified view of ($\bar{1}01$) twin lamellae in Fig. 1. The NE-SW (100) cleavages are deflected at twin boundaries by the twinning shear. White areas within ($\bar{1}01$) twin lamellae are (100) twins.

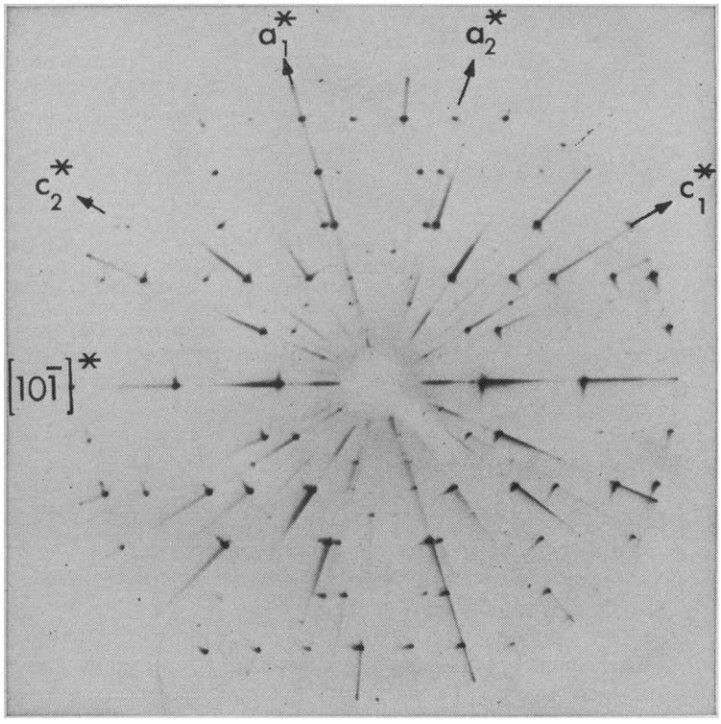



Fig. 3. An x-ray precession photograph of the ($h0\ell$) net of a deformed hornblende (A1-59T). Molybdenum radiation, Zr-filtered, 18-hour exposure. Test conditions were 15 kb and 600°C.

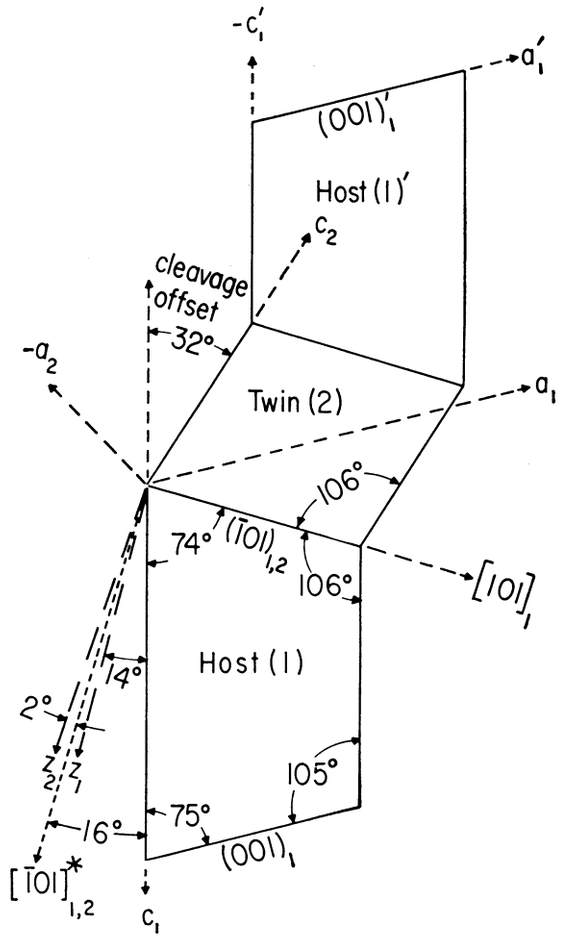



Fig. 4 (right). The relationships between the crystallographic axes, twin axis, and Z optic-vibration direction in host and twin. Diagram is based on C-centered clinoamphibole cell. Measured values of $\beta$ are 105°0′ (C-cell) and 106°21′ (I-Cell). $c_1 \wedge \bar{1}01 = 73°40'$ (C-cell).

tions, the crystallographic axes, and the orientation of the exsolution and twin lamellae. Significantly, all the ($\bar{1}01$) lamellae thus far observed in natural amphiboles are caused by exsolution and are not due to twinning. Therefore, some doubt has arisen that ($\bar{1}01$) twinning exists in clinoamphiboles. As part of an experimental program to assess the mechanical properties of amphiboles (*3*), we report the experimental production of deformation twins on ($\bar{1}01$) in single crystals of hornblende.

We used a solid-pressure-medium apparatus (*4*) to deform cylindrical specimens approximately 7.7 mm long and 2.8 mm in diameter at confining pressures to 20 kb and temperatures to 1200°C. All experiments were made at a constant strain rate of $10^{-5}$ per second. The hornblende, from Bamle, Norway (*5*), is a common calciferous aluminous variety whose formula, calculated from chemical analysis (*6*), is: $(Na_{.37}K_{.13})_{\Sigma.50}(Ca_{1.74}Na_{.23})(Mg_{2.76}Fe^{2+}_{1.41}Fe^{3+}_{.41}Ti_{.22}Al_{.22}Mn_{.01})_{\Sigma5.03}(Si_{6.65}Al_{1.35})_{\Sigma8.00}O_{22}(OH,Cl,F)_2$. Least squares refinement (*7*) of the x-ray powder data gives the following unit-cell: $a = 9.885$ Å, $b = 18.169$ Å, $c = 5.299$ Å, and $\beta = 104°43'$.

The evenly spaced twin lamellae in the deformed hornblende sample are approximately 0.02 to 0.06 mm thick and are developed profusely along the entire length of the sample (Fig. 1). The trace of the ($\bar{1}01$) twin lamellae (Fig. 1) is the composition plane and is parallel, within the accuracy of measurement on the universal stage, to the ($\bar{1}01$) twin plane. The long axis of the cylinder is parallel to $\sigma_1$, the direction of maximum compression, and to the *c* crystallographic axis of the hornblende single crystal. Twinning was not induced in crystals compressed parallel to other crystallographic directions.

Although twins formed at all confining pressures, they are most abundant and best developed at 15 kb (Table 1). The shear strain calculated from rotation of the (100) cleavage planes is 0.53. The resolved shear stress required to twin amphibole on ($\bar{1}01$) is 2 to 4 kb at the conditions of our tests.

The extinction directions in host and twin are almost parallel (Fig. 2). Universal stage measurements of the directions of optical vibration confirm this observation. In addition, the ($\bar{1}01$) twin lamellae contain areas twinned on (100). Apparently, the (100) planes initially parallel to the compression axis are rotated by shear on ($\bar{1}01$) into an orientation of high shear stress that favors twinning on (100).

The twinning observed by optical methods was verified by taking an x-ray precession photograph of the ($h0\ell$) net (Fig. 3). The amphibole is twinned about [$\bar{1}$01]* with the twin planes parallel to ($\bar{1}01$) and the direction of slip along the plus [101] direction (*8*) (Fig. 4). Additional reflections not visible in Fig. 3 confirm a small amount of (100) twinning.

The similar extinction angles for the host and twin lamellae are explained in Fig. 4. Since the directions of Z vibration ($Z \wedge c = 14°$) for host and twin depart from the [$\bar{1}$01]* twin axis by 2 degrees, the difference in extinction is only 4 degrees. The calculated angle between the (100) cleavage traces (Fig. 4) is 32°; the observed angle is 28°.

Knowledge of plastic deformation mechanisms is useful because the orien-

tation of principal stress axes often can be deduced by analysis of translation and twin gliding features in minerals from deformed rocks. However, Carter and Raleigh (*9*) state that "amphiboles in tectonites rarely show any signs of plastic deformation." Our experiments suggest that the high stresses required for twinning accounts for the scarcity of ($\bar{1}01$) twins in naturally deformed amphiboles. We have observed ($\bar{1}01$) lamellar structures in shocked amphiboles from the Vredefort dome, and Chao (*10*) reports closely spaced planar structures in hornblende from a moderately shocked plagioclase amphibolite. We suggest that twinning may be a significant mechanism of deformation in shocked amphiboles.

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## Anomalous Water: Attempts at High-Pressure Synthesis

Abstract. *The high density, 1.4 grams per cubic centimeter, reported for anomalous water suggests that high pressures should be conducive to the formation of anomalous water. Six attempts at 60 kilobars in which water was cooled from about 600°C in nickel or platinum tubes, with or without the presence of silica, did not produce any detectable amounts of anomalous water.*

The reports of Deryagin and Churayev (*1*) on a new, dense form of water with unusual properties has stimulated considerable experimentation (*2, 3*) and a surprising amount of theoretical speculation (*4*) on its structure. Lippincott *et al.* (*2*) proposed that the substance was a special, polymeric form of $H_2O$ and suggested the name "polywater" for it. Only small amounts of this substance have been prepared by a method presumably based upon the condensation of water in small glass or vitreous silica tubes. Some recent work (*5*) has demonstrated the difficulties associated with the production of pure water of any kind by the conventional methods used for producing anomalous water, and it is possible that many of the unusual properties of polywater are the result of dissolved or suspended impurities.

It would be helpful to have larger samples, for example, 0.1 g, of polywater available for research. Leiga *et al.* (*6*) attempted to prepare it by a gaseous discharge method but obtained mainly an aqueous solution of nitric acid.

The reported relatively high density, 1.4 g $cm^{-3}$, of polywater suggests that high pressures ought to aid its formation. At room temperatures, compressed water ordinarily freezes as different forms of ice (*7*). Above about 23 kb Ice VII is stable, and Bridgman (*8*) found that its melting temperature goes from about 80°C at 23 kb to about 190°C at 40 kb. At 20°C and 50 kb the density of Ice VII is about 1.67 g $cm^{-3}$. However, no polywater has ever been reported as a result of the cold compression of water, perhaps because the solid state limits molecular rearrangement or perhaps because nobody thought to look.

In a recent discussion with E. U. Franck the possibility was considered of forming polywater by heating water to above 600°C at 60 kb, where it would be liquid with a density of at least 1.4 g $cm^{-3}$, and then cooling it under pressure so as to give it the maximum opportunity to form thermodynamically favored dense liquid phases.

The "belt" high-pressure apparatus (*9*) was used in these attempts. The water was contained in a nickel or platinum capsule about 3 mm in diameter and 10 mm long which was surrounded by pyrophyllite and heated electrically. Pressures were estimated by reference to calibrations with barium and bismuth in the usual way, and temperatures were estimated from the heating power dissipated in the samples. The temperature was raised to the range 500° to 700°C in a few minutes and reduced from its maximum to 25°C in about 7 minutes. The samples recovered were immediately placed in screw-capped vials pending further analysis.

Six attempts at high-pressure synthesis were made, four in nickel tubes and two in platinum. The platinum tubes could be recovered intact, but the hot water corroded the nickel slightly and made it brittle so that the nickel tubes were torn into three segments by the forces generated during pressure release. Part of the water thereby moistened adjacent fragments of pyrophyllite, but some water remained in the nickel tubes as they were placed, together with the moist pyrophyllite, in the glass vials. In one experiment with a nickel tube and one with platinum, one or two small fragments of vitreous silica were placed in the tube along with the water to serve as catalysts for the formation of polywater.

The infrared spectrum of a specimen of liquid from the plain platinum (no $SiO_2$) tube exhibited two of the peaks of normal water and no anomalous water peaks, although the specimen had nearly evaporated by the time the spectrum had been swept (*10*). The literature on polywater indicates that it should not evaporate this easily. The specimen from the platinum tube containing $SiO_2$ evaporated before its infrared spectrum could be obtained. The piece of $SiO_2$ left was opaque and white with a density exceeding 2.8 g $cm^{-3}$ and was identified from its refractive index as coesite. The formation of coesite indicates that both water and silica were active in this experiment (at least 550°C), but no significant amounts of polywater were obtained.

The glass vials containing the products from the nickel tube were placed in a refrigerator at 2°C; all of them soon acquired a film of liquid droplets on their inside walls and no liquid