

FIG. 114. Dependence of magnetization σ on the applied field, H at several different temperatures, with the field $//Z$, for arfvedsonite(80) [from Borg & Borg (1980)].

the elastic-energy density U of a crystal is a quadratic function of the strains (Kittel 1966); thus

$$U = 1/2 \sum_{i=1}^6 \sum_{j=1}^6 \tilde{C}_{ij} e_i e_j$$

where the indices $1 \rightarrow 6$ are defined as:

$$1 \equiv 11; 2 \equiv 22; 3 \equiv 33; 4 \equiv 23; 5 \equiv 31; 6 \equiv 12.$$

The stress components are found from the first derivative of U with respect to the associated component of strain:

$$X_i = \frac{\partial U}{\partial e_{ii}} \cdot \frac{\partial U}{\partial e_i} = \tilde{C}_{ii} e_i + 1/2 \sum_{j=1, j \neq i}^6 (\tilde{C}_{ij} + \tilde{C}_{ji}) e_j$$

As only the combination $1/2 (\tilde{C}_{ij} + \tilde{C}_{ji})$ enters

the stress-strain relationship, the elastic stiffness constants must be symmetrical:

$$C_{ij} = 1/2(\tilde{C}_{ij} + \tilde{C}_{ji}) = C_{ji}$$

Thus the thirty-six elastic-stiffness constants are reduced to twenty-one. The presence of crystallographic symmetry requires that the elastic-energy density U be invariant under all symmetry operations of the relevant point-group. Thus for the clin amphiboles

$$C_{14} = C_{16} = C_{24} = C_{26} = C_{34} = C_{36} = C_{45} = C_{56} = 0$$

leaving thirteen unique nonzero elastic-stiffness constants. The only detailed work on the amphiboles is that of Aleksandrov & Ryzhova (1961), who determined the elastic properties of two "hornblendes". The data are presented in Table 69, together with the available mineralogical data for the amphiboles used in the work. The moduli of elasticity C_{11} , C_{22} and C_{33} represent pure compression $// X^*$, Y and Z , respectively. In both examples, C_{11} is significantly less than C_{22} and C_{33} , indicating that the structures are most easily compressed along X^* . Examination of Figure 9 suggests that this may be the result of compression of the A-site cavity along X^* with the I-beam units themselves compressing much less. If this is the case, one might expect considerable variations in C_{11} throughout the amphiboles, depending on whether or not the A site is occupied. C_{44} , C_{55} and C_{66} are pure-shear moduli $// YZ$, X^*Z and X^*Y , respectively. In both samples, C_{44} is significantly greater than C_{55} and C_{66} , indicating more resistance to shear in the YZ plane than in the other planes.

The early work of Adams & Williamson (1923) has been summarized by Birch (1966): for the expression $\Delta V/V = aP$ (where V = volume, ΔV = change in volume, P = pressure in megabars), hornblende has the value a in the range 1.1 - 1.2, and actinolitic amphibole has the value $a = 1.3$, which is the mean value over a range from 2 to 12 kbar.

DEFORMATION BEHAVIOR OF AMPHIBOLES

Deformation behavior of nonasbestiform amphiboles in natural rocks is generally of the brittle type, although ductile deformation can occur (Gavasci 1973). In most tectonites, where most of the constituent minerals show ductile

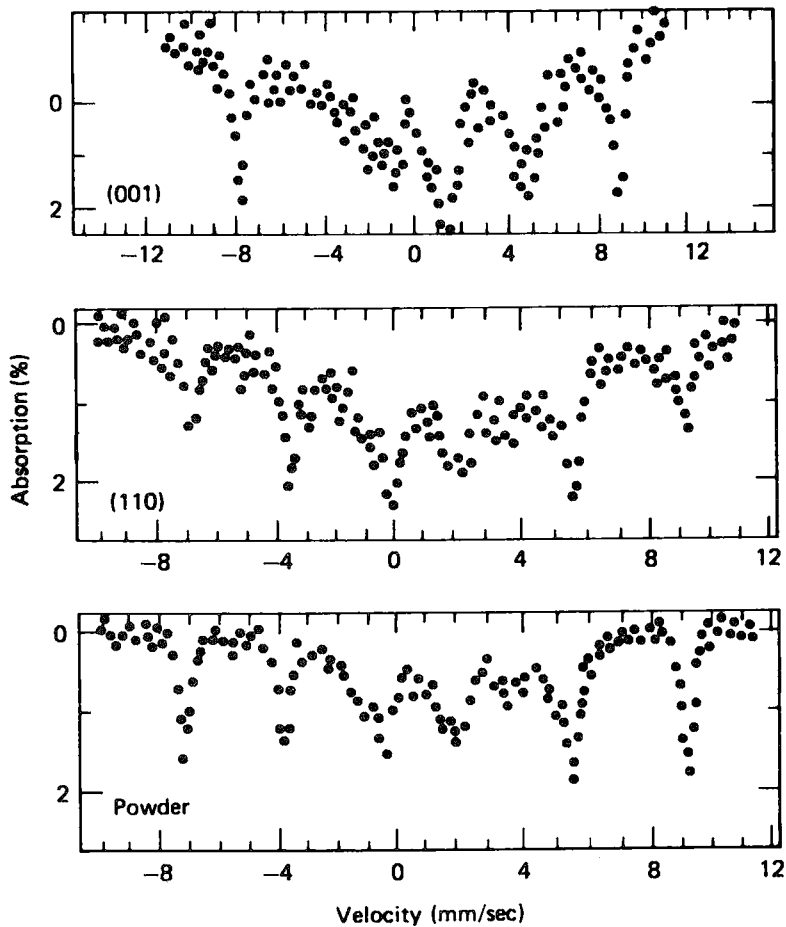


FIG. 115. Magnetic hyperfine spectra of arfvedsonite{80} at 4 K. Top: single-crystal spectrum, oriented $//(001)$; middle: single-crystal spectrum, oriented $//(110)$; bottom: powder spectrum, [Borg & Borg (1980)].

behavior, plastic deformation of amphibole is very uncommon (Carter & Raleigh 1969). Experimental work has shown that plastic deformation can be produced in amphiboles but that amphiboles have very high strength. A typical shear-strength curve for an edenitic hornblende (Table 70) is shown in Figure 116; Rooney & Riecker (1969) indicated that the true shear strength in this example is shown by tests 25 at 500°C and 30 at 900°C. The low pressure - low temperature data of Figure 116 do not represent true shear strength, being strongly affected by surface friction, *etc.*, but indicate that the amphibole is extremely strong and shows brittle or cataclastic deformation under these conditions. Isothermal and isobaric stress-strain curves for the same edenitic hornblende are

shown in Figure 117. As indicated in the isobaric curves, there is a considerable weakening at higher temperatures. Rooney *et al.* (1974) suggested that this is due to dehydration of the amphibole, causing both a reduction in the intrinsic strength of the amphibole and a rise in the pore pressure (from the evolved fluids) that lowers the effective confining pressure and reduces strength. Inspection of the isothermal curves shows that at confining pressures above 15 kbar, edenitic hornblende is notably weaker than at lower confining pressures; similar behavior was also observed for tremolite (Rooney *et al.* 1974). This weakening is probably due to dehydration of the amphibole at high pressure, as experimental studies (Mysen & Boettcher 1975) have shown that $\partial P/\partial T$ for the amphi-

TABLE 69. ELASTIC CONSTANTS FOR AMPHIBOLES

Hornblende I		Hornblende II		
2V	-82 ⁰	+83 ⁰		
$\gamma_{\wedge Z}$	25.2 ⁰	29.7 ⁰		
$\gamma^{-\alpha}$	0.014	0.016		
D(g/cm ³)	3.124	3.153		
i j	C _{ij} [*]	S _{ij} ^{**}	C _{ij} [*]	S _{ij} ^{**}
1 1	1.160	1.0868	1.301	1.1368
2 2	1.597	0.7684	1.877	0.6582
3 3	1.916	0.6929	1.984	0.8637
4 4	0.574	1.7745	0.611	1.6371
5 5	0.318	3.2285	0.387	3.8180
6 6	0.368	2.7678	0.450	2.2229
1 2	0.449	-0.1925	0.614	-0.2648
1 3	0.614	-0.2786	0.592	-0.4126
2 3	0.655	-0.2089	0.614	-0.1112
1 5	0.043	-0.0745	0.095	-0.7591
2 5	-0.025	0.1521	-0.069	0.0656
3 5	0.100	-0.1966	-0.406	0.9875
4 6	-0.062	0.2990	-0.009	0.0327

* elastic stiffness coefficients in megabars;

** elastic compliance constants in reciprocal megabars. Data of Aleksandrov & Ryzhova (1961).

bole dehydration curve changes sign at high pressures (above 15 kbar). Experiments with the maximum stress at 45° to [001] showed that amphiboles are less than half as strong in this direction than along [001]; in these cases, failure always occurred along cleavages, even at the highest confining pressures (Rooney & Riecker 1973).

Although rare in natural rocks, plastic deformation features in amphiboles have been produced in many studies (Borg & Handin 1966, Buck & Paulitsch 1969, Rooney & Riecker 1969, Buck 1970). Twinning on ($\bar{1}01$) is the dominant deformation mode in compression with σ_1/Z at confining pressure from 5 to 15 kbar and temperatures from 400 to 600°C. Rooney *et al.* (1970) confirmed the twinning by X-ray precession photography of experimentally deformed single crystals. Rooney *et al.* (1974) gave the twin system as $K_1 = (\bar{1}01), N_1 = [\bar{1}0\bar{1}], K_2 = (100), N_2 = Z$, but Kirby & Christie (1977) indicated that $N_2 = -Z$. Rooney *et al.* (1975) also reported translation gliding on (100) parallel to Z when the direction of principal stress is not parallel to Z. Morrison-Smith (1976) studied the deformed amphiboles of Rooney *et al.* (1974) using transmission electron microscopy (TEM). This confirmed the importance of ($\bar{1}01$) defor-

TABLE 70. CHEMICAL AND UNIT-CELL DATA ON EDENITIC HORNBLLENDE, DEFORMATIONAL DATA FOR WHICH ARE GIVEN IN FIGURES 116 AND 117.

Analysis		Formula Unit	
SiO ₂	45.14	Si	6.652
TiO ₂	1.99	Al	<u>1.348</u>
Al ₂ O ₃	9.02	ΣT	8.000
Fe ₂ O ₃	3.74	Al	0.219
FeO	11.45	Ti	0.220
MnO	0.09	Fe ³⁺	0.414
MgO	12.56	Fe ²⁺	1.411
CaO	10.99	Mg	2.759
Na ₂ O	2.11	Mn	<u>0.012</u>
K ₂ O	0.71	ΣC	<u>5.035</u>
P ₂ O ₅	0.01		
H ₂ O ⁺	1.62	$\Sigma C-5$	0.035
H ₂ O ⁻	0.05	Ca	1.735
CO ₂	-	Na	<u>0.230</u>
Cl	0.51	ΣB	<u>2.000</u>
F	<u>0.16</u>		
	100.15	Na	0.372
O≡F, Cl	<u>0.19</u>	K	<u>0.133</u>
Σ	<u>99.96</u>	ΣA	<u>0.505</u>
a	9.885Å	OH	1.592
b	18.169	Cl	0.128
c	5.299	F	<u>0.074</u>
β	104.72 ⁰	$\Sigma O(3)$	<u>1.794</u>
V	920.5Å ³		

mation twins as the principal type of deformation. The twins commonly contain a high density of dislocations, the predominant slip-system being (100) Z; this was explained in terms of Z being the shortest possible Burgers vector and (100) slip planes requiring the lowest density of broken bonds. Associated with such dislocations are linear arrays of disk-like (100) platelets of exsolved amphibole, interpreted as being preferentially formed in the local stress field of the dislocation. Such features have also been observed in naturally deformed amphiboles (Morrison-Smith 1974). Morrison-Smith (1976) interpreted the deformation twinning as a martensitic-type shear requiring very little diffusion of atoms. The mechanism is illustrated in Figures 118 and 119. The tetrahedral layers are rotated ~30° about a series of pivot points (P₁, P₂...), with shear occurring within the octahedral layer, the upper layers of oxygen atoms (O-O_F in Fig. 119) being displaced with

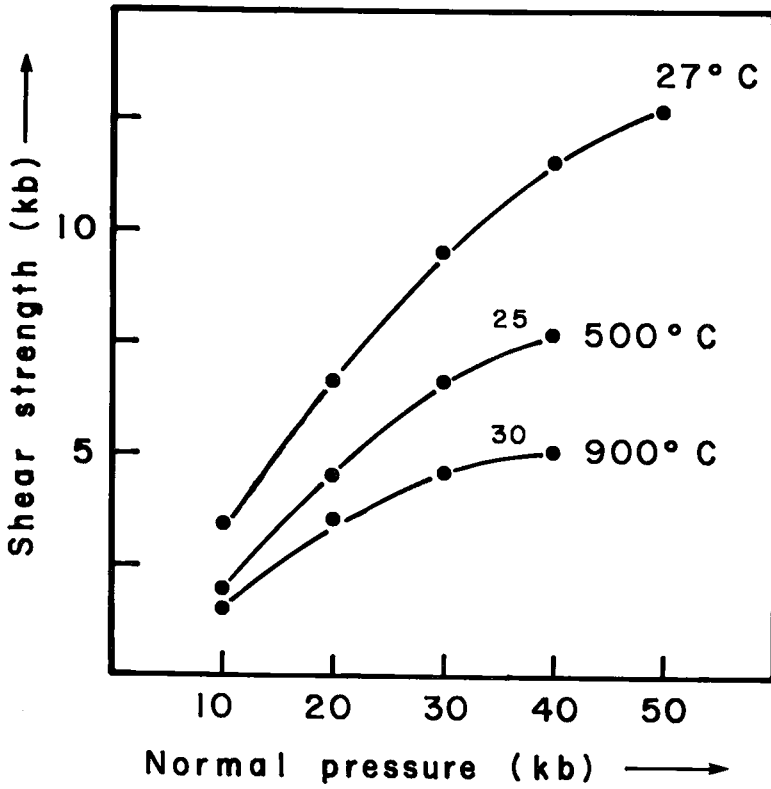


Fig. 116. Shear strength as a function of normal pressure for an edenitic hornblende, compositional details of which are given in Table 71 [after Rooney & Riecker (1969)].

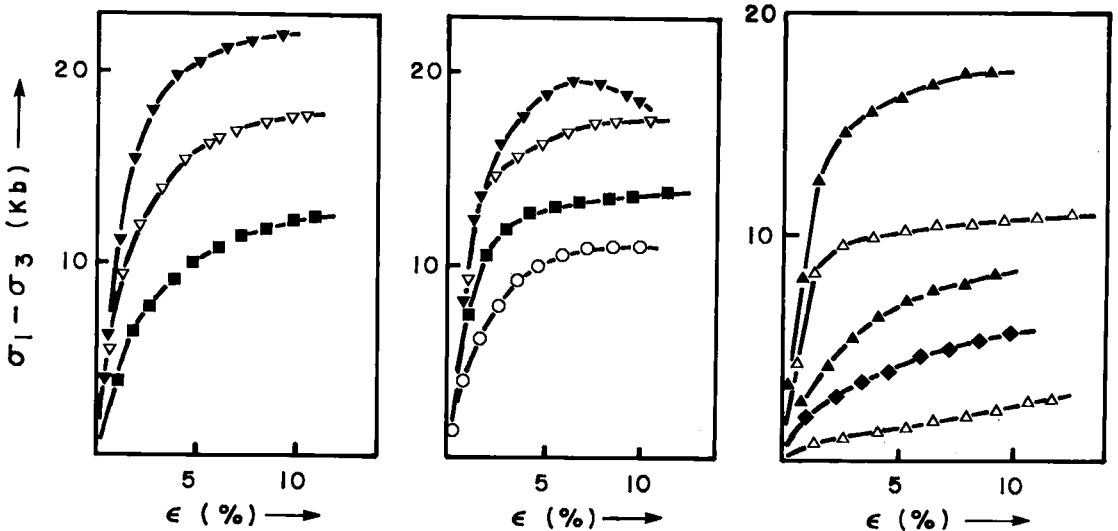


Fig. 117. Isothermal (left and middle) and isobaric (right) stress-strain curves for single-crystal edenitic hornblende (Table 71) [after Rooney & Riecker (1973) and Rooney *et al.* (1974).]

respect to the lower (O_I-O_K). At the twin boundary, the tetrahedral linkage is continuous, whereas the octahedral strips are interrupted. Dollinger & Blacic (1975) experimentally deformed a hornblendite to produce kink bands whose orientation is consistent with glide on (100); at lower temperatures (600–750°C), the glide direction is //Z, but at higher temperatures (800–850°C), the glide directions are confined to (100) only. Observations on naturally deformed (bent) actinolite crystals also suggest the same glide-mechanism for the formation of bent amphibole crystals. Dollinger & Blacic (1975) suggested that the previous experimental studies produced twinning because compression //Z results in zero resolved shear-stress on the (100) Z glide system, and thus the experimental conditions of these studies would not produce such a glide deformation. They also suggested, as did Rooney *et al.* (1975), that this glide mechanism accounts for the much weaker strength of amphibole when the direction of principal stress is not parallel to Z, as the

TABLE 71. JOESMITHITE SITE-NOMENCLATURE PROPOSED HERE COMPARED WITH THAT USED BY MOORE (1969)

New	Old	New	Old
O(1)A	O(4)	O(1)B	O(2)
O(2)A	O(5)	O(2)B	O(1)
O(3)	O(3)	-	-
O(4)A	O(12)	O(4)B	O(6)
O(5)A	O(10)	O(5)B	O(7)
O(6)A	O(11)	O(6)B	O(8)
O(7)	O(9)	-	-
M(1)A	M(1')	M(1)B	M(1)
M(2)A	M(2')	M(2)B	M(2)
M(3)	M(3)	-	-
M(4)A	M(4')	M(4)B	M(4)
A(2)	A	-	-
T(1)A	Si(2)	T(1)B	Be
T(2)A	Si(1)	T(2)B	Si(3)

glide mechanism occurs at a lower critical resolved shear-stress than the twinning mechanism. In a similar study, Nielson & Ross (1979)

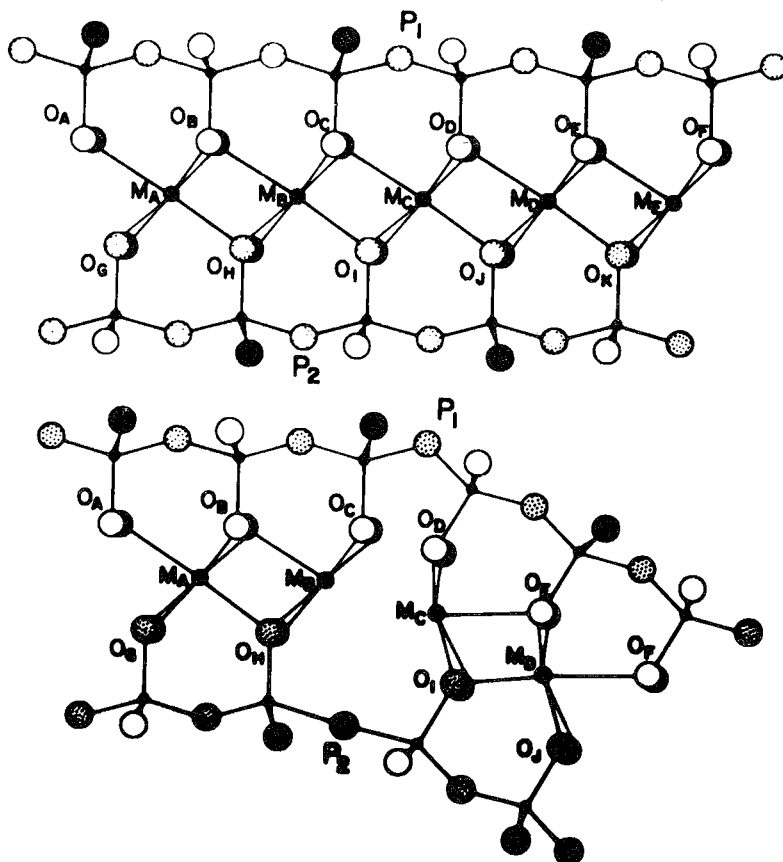


FIG. 118. Schematic (010) view of composition plane of hornblende twinned on (101); the points P lie on the composition plane [from Morrison-Smith (1976)].

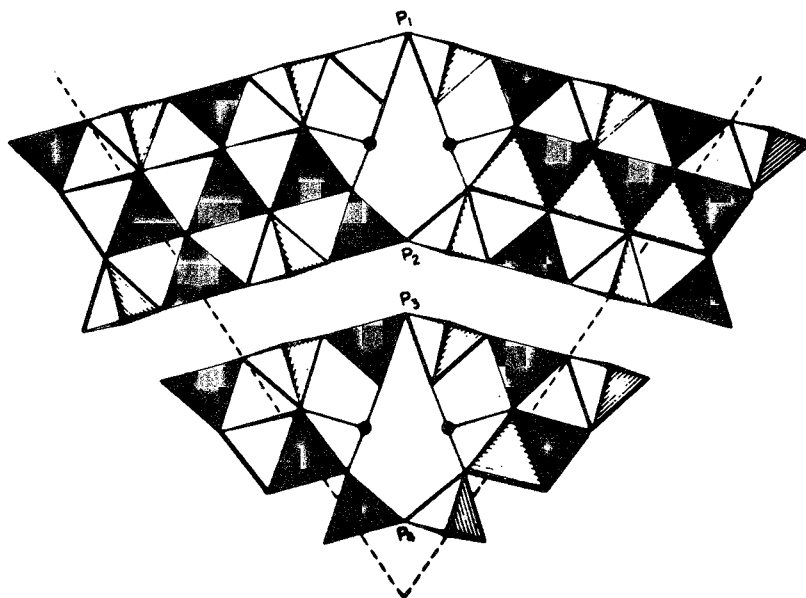


Fig. 119. Sections (010) through a single tetrahedral-octahedral layer (upper) and a twinned layer (lower), showing the bond re-arrangements required [from Morrison-Smith (1976)].

found both mechanical twinning and translation gliding to have occurred; they showed that twinning was favored by higher confining pressure, lower temperature and higher strain rate. This is in agreement with the occurrence of mechanically twinned amphiboles in shock environments (Chao 1967, Borg 1972). Biermann (1981) described (100) twins in hornblende produced by natural deformation, and confirmed the absence of $(\bar{1}01)$ twins. Associated defects include long arrays of dislocations parallel to the trace of the (100) planes. A twinning mechanism similar to that suggested for pyroxenes (Kirby & Christie 1977) was proposed for the amphiboles (Biermann 1981). There is rigid translation of tetrahedral layers $//Z$ by an amount $c/2$, with simple shear deformation of the intervening octahedral layers. The twinning shear can be propagated by the movement of partial dislocations with $\bar{b} = \frac{1}{2} Z$ gliding in the octahedral layer. Thus the result is a deformation twin with b -glide symmetry on (100).

SUMMARY

The general outlines of amphibole crystal-chemistry are now in place. Most principal amphiboles have been characterized by crystal-

structure refinement and miscellaneous spectroscopic studies, and our knowledge of the general cation-ordering patterns and stereochemical variations is reasonably complete. Some specific questions still remain to be solved, but these are fairly tractable by conventional crystallographic and spectroscopic techniques, and can soon be answered. There is much interesting spectroscopic work still to do, particularly in the area of electronic-absorption spectroscopy and intervalence charge-transfer; however, this situation is not particularly limited to the amphiboles. The principal area of expansion is in the application of amphibole crystallography and crystal chemistry to problems in petrology.

The complex interrelationships between cation ordering, mineral composition and ambient chemical environment should be very responsive to differences in physical and chemical conditions of crystallization and equilibration. It has been customary to emphasize the great potential significance of amphiboles in this respect. Sufficient information is now available concerning amphibole crystal chemistry to change this potential significance into real significance. Rather than examining variations in mineral composition (exclusive of Fe^{3+} and $\text{H}_2\text{O}/\text{F}$) with changing environment, examination of variations in cation ordering, crystal structure and

composition (including Fe^{8+} and H_2O) with changing environment provides much more information. Such investigations have already begun (Ungaretti *et al.* 1981) and promise to expand in the future, coupled with corresponding work on coexisting minerals. These studies will be expensive and will require a change in the general perception of the relationships between crystallography, mineralogy and petrology; the result will be a better characterization of petrologic processes.

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