

## ON BABINGTONITE

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The granite pegmatites of Blueberry Mountain, Woburn, Massachusetts, contain small veins filled with calcite and lined with excellent crystals of the rare mineral babingtonite, a metasilicate of lime and iron with essential hydroxyl, which has generally been classed as a triclinic pyroxene. The occurrence and appearance of these crystals have been described in a recent paragenetic study (1937); the object of the present paper is to record the results of a more detailed morphological, roentgenographic and optical study which leads to a definitive statement of the crystallography of the species and points to its systematic relations.

In a recent paper on axinite Peacock (1937) has proposed a unique setting for triclinic crystals, named the *normal setting*, which conforms to generally accepted morphological and structural requirements. In this setting the lattice elements correspond to the simple cell defined by the three shortest non-coplanar identity periods of the structural lattice, in the one position out of twenty-four in which the vertical cell-edge is the axis of the main morphological zone, the axial angles  $\alpha$  and  $\beta$  are both obtuse, and the axial length  $b[010]$  is longer than the axial length  $a[100]$ . Peacock shows how this unique setting can be reached by inspection of the gnomonic projection of the crystal forms on the plane normal to the axis of the main zone; and he proves the validity of the method in the case of axinite by showing that an independent determination of the structural lattice leads to absolute elements which are geometrically similar to those obtained from the morphology. The newly found babingtonite crystals afford an opportunity to apply Peacock's procedure for finding the normal setting and test the propriety of this setting in another typical case.

*The normal setting of babingtonite.* Crystals suitable for morphological, structural and optical study were obtained by dissolving the calcite matrix in hydrochloric acid. The residue yielded babingtonite crystals ranging from 0.1 mm. to 1.0 mm. in size. The crystals are black with bright faces giving good reflections. The smallest crystals, all of which are doubly terminated, proved most suitable for study; they are short-prismatic in habit, somewhat flattened parallel to the axis of elongation, and richer in forms than the crystals of larger size. The axis of the zone of prismatic development is also the axis of the zone which is most commonly the main zone of babingtonite; this zone is therefore properly set vertically.

Figure 1 gives a gnomonic projection of the known forms of babingtonite on the plane normal to the chosen vertical axis. The plane of the gnomonic projection is considered as the first layer  $|hk1|$  of the reciprocal lattice. Vertical planes  $(hk0)$  are represented by radial lines drawn from  $c(001)$  to  $(hk1)$ , the point  $(hk1)$  being inserted as a blank point, as in  $m f j h$ , when it does not represent a known terminal form. The radial lines are thus normal to the respective vertical planes, and their lengths are inversely proportional to the spacings and reticular densities of the corresponding planes in the direct lattice.

The reciprocal structural lattice is determined when we have properly distinguished the first layer points  $(hk1)$ , which are actually in the plane of the gnomonic projection, from the higher layer points  $(hkn)$  which appear in fractional positions on the plane of the gnomonic projection. This is simply done, in the present case, by taking as the first layer points those points which form a plane lattice without systematic omissions. This condition permits of only one choice: the large filled points  $c r q d n s o p e k$  must be the first layer points; the small blank points  $y x v w u i t$ , all of which represent weak forms, are therefore points in higher layers of the reciprocal lattice.

To obtain the desired representative lattice cell, whose axial planes are the three non-tautozonal planes with the greatest spacings, and whose respective reciprocal lattice points are therefore the three non-colinear points nearest the origin, we choose the first-layer point nearest the center  $c$ , as the axial plane  $(001)$ ; the first-layer point nearest to  $c$ , namely  $d$ , is taken as  $(011)$ ; the next nearest, not in the zone  $[cd]$ , namely  $r$ , is taken as  $(101)$ . All the points in the projection can now be immediately indexed; and the chosen cell meets the stated conditions. The vertical axis is the axis of the main zone; the pole of the base lies in the first quadrant, hence  $\alpha$  and  $\beta$  are both obtuse; and the reciprocal lattice period  $q_0' = c - d$  is less than the period  $p_0' = c - r$  giving  $b[010]$  greater than  $a[100]$ . The chosen cell, therefore, stands in the unique orientation of the normal setting. If this had not been the case, the desired orientation would be reached by turning the projection about the vertical axis, or by inverting it and then turning it into the one position in which the stated conditions are satisfied.

In the normal position two circle measurements on fifteen crystals give the projection elements:

$$p_0' = 0.9273, q_0' = 0.5934; x_0' = 0.0671, y_0' = 0.0456; \nu = 75^\circ 42\frac{1}{2}'$$

which give, by calculation, the following polar and linear elements:

$$p_0 : q_0 : r_0 = 0.9242 : 0.5915 : 1; \lambda = 87^\circ 23\frac{1}{2}', \mu = 85^\circ 38', \nu = 75^\circ 42\frac{1}{2}' \\ a : b : c = 0.6411 : 1 : 0.5747; \alpha = 91^\circ 28', \beta = 94^\circ 12', \gamma = 104^\circ 11'.$$

Figure 2 shows a typical babingtonite crystal from Woburn, drawn in the position corresponding to the normal setting. The position is in every way satisfactory. The largest planes are  $m(110)$ ,  $a(100)$ ,  $M(\bar{1}\bar{1}0)$ . The base  $c(001)$  is also fairly large. The side-pinacoid,  $b(010)$  is narrow; but this is one of the vagaries of morphological development for which there is no explanation and which should not influence the choice of elements. Even if the side-pinacoid had been absent, the above method for finding the normal setting would have led to the same result. The cleavages are  $\{001\}$  perfect, and  $\{\bar{1}\bar{1}0\}$  imperfect, which correspond respectively to the third and fourth greatest lattice spacings. The most common morphological elongation is in the direction of the shortest axis  $c[001]$ , and therefore in the direction of the densest lattice row.

In the normal setting the forms observed on the crystals studied are:

$c\{001\}$ ,  $b\{010\}$ ,  $a\{100\}$ ,  $m\{110\}$ ,  $f\{210\}$ ,  $M\{\bar{1}\bar{1}0\}$ ,  $h\{\bar{1}\bar{2}0\}$ ,  $d\{011\}$ ,  $n\{0\bar{1}1\}$ ,  $r\{101\}$ ,  $q\{\bar{1}01\}$ ,  $s\{\bar{1}\bar{1}1\}$ ,  $o\{\bar{1}11\}$ ,  $p\{\bar{1}21\}$ , the new forms:  $j\{310\}$ ,  $e\{\bar{1}\bar{1}1\}$ ,  $k\{\bar{1}21\}$ ; and the new but uncertain forms:  $\{350\}$ ,  $\{121\}$ .

The prominent forms are  $a c m f M h d n q s o$ , most of which occur on all the crystals. The new forms,  $j e k$ , appear as small faces in good position, as shown by the agreement in Table 1. The two uncertain forms were observed only once each.

TABLE 1. BABINGTONITE: NEW FORMS

| Form                 | Number of faces | Measured |        | Calculated |         |
|----------------------|-----------------|----------|--------|------------|---------|
|                      |                 | $\phi$   | $\rho$ | $\phi$     | $\rho$  |
| $j(310)$             | 3               | 64°35'   | 90°00' | 64°42'     | 90°00'  |
| $e(\bar{1}\bar{1}1)$ | 5               | -133 42  | 48 49  | -133 02½   | 48 38½' |
| $k(\bar{1}\bar{2}1)$ | 3               | -148 24  | 58 22  | -148 45    | 58 00   |

*Correlation of morphological settings.* Babingtonite has been variously oriented by Dauber (1855), Dana (1892) and Goldschmidt (1897-1922). Dauber's position, which was adopted by Palache & Frapje (1902) and by Palache & Gonyer (1932) refers to a cell of the structural lattice; but the choice and orientation of the cell does not conform to the normal triclinic setting. The relation of Dauber's setting to the normal setting, in the gnomonic projection and the direct lattice, is shown in figures 3, 4, in which the dotted cells and underlined symbols are those of Dauber. The settings of Goldschmidt and Dana were intended to bring out morphological analogies, and they depart even farther from the normal setting. The elements and indices of the four settings (Dauber, Dana, Goldschmidt, Richmond) are related by the transformation formulas in

Table 2, which is arranged in a double-entry form suggested by Professor J. D. H. Donnay.

TABLE 2. BABINGTONITE: TRANSFORMATION FORMULAS

| To \ From   | Dauber (1855)           | Dana (1892)             | Goldschmidt (1897)      | Richmond                |
|-------------|-------------------------|-------------------------|-------------------------|-------------------------|
| Dauber      |                         | 0 0 4<br>1 1 0<br>1 1 0 | 0 0 1<br>1 0 0<br>0 1 0 | 1 1 0<br>1 0 0<br>0 0 1 |
| Dana        | 0 2 2<br>0 2 2<br>1 0 0 |                         | 2 2 0<br>2 2 0<br>0 0 1 | 2 0 2<br>2 0 2<br>1 1 0 |
| Goldschmidt | 0 1 0<br>0 0 1<br>1 0 0 | 1 1 0<br>1 1 0<br>0 0 4 |                         | 1 0 0<br>0 0 1<br>1 1 0 |
| Richmond    | 0 1 0<br>1 1 0<br>0 0 1 | 1 1 0<br>1 1 4<br>1 1 0 | 1 0 0<br>1 0 1<br>0 1 0 |                         |

To show how this table is used to find the indices ( $h'k'l'$ ) in a desired setting from the given indices ( $hkl$ ) in another setting, let us transform Dana's  $f\{443\}$  to Richmond's setting. From Table 2 the required transformation formula, from Dana to Richmond, is:  $110/114/110$ . Then  $h' = 1 \times 4 + 1 \times 4 + 0 \times 3 = 8$ ;  $k' = 1 \times 4 + 1 \times 4 + 4 \times 3 = 4$ ;  $l' = 1 \times 4 + 1 \times 4 + 0 \times 3 = 0$ . The new indices are thus (840) or (210) which is a plane of our form  $f\{210\}$ .

Table 3 shows the forms of babingtonite observed or recorded by Dauber, Dana, Goldschmidt, Palache, Richmond, and correlates the signatures of the several authors.

Transforming the elements of Dauber to the normal setting, according to the transformation formula: from Dauber to Richmond: 010/110/001, we obtain:

$$a:b:c = 0.6417:1:0.5746; \alpha = 91^\circ 31', \beta = 93^\circ 51', \gamma = 104^\circ 04'$$

The elements from the new measurements are:

$$a:b:c = 0.6411:1:0.5747; \alpha = 91^\circ 28', \beta = 94^\circ 12', \gamma = 104^\circ 11'$$

The two sets of elements agree so closely that Dauber's transformed values are adopted in the formal angle-table for the known forms of babingtonite in the normal setting (Table 4).

*Optics.* The optical properties of the Woburn babingtonite were determined on small crystals mounted on the universal stage, and by the immersion of fragments. Due to the excessively strong absorption of the mineral it proved difficult, yet possible, to find crystals small enough to

TABLE 3. BABINGTONITE: CORRELATION OF FORM LETTERS

|                        | Dauber<br>(1855) | Dana<br>(1892) | Goldschmidt<br>(1897-1922) | Palache<br>(1902-1932) | Richmond   |
|------------------------|------------------|----------------|----------------------------|------------------------|------------|
| <i>c</i> 001           | <i>c</i>         | <i>M</i>       | <i>c</i>                   | <i>c</i>               | <i>c</i>   |
| <i>b</i> 010           | <i>a</i>         | <i>c</i>       | <i>a</i>                   | <i>a</i>               | <i>b</i>   |
| <i>a</i> 100           | —                | —              | <i>k</i>                   | <i>k</i>               | <i>a</i>   |
| <i>m</i> 110           | <i>g</i>         | <i>g</i>       | <i>r</i>                   | <i>g</i>               | <i>m</i>   |
| <i>f</i> 210           | —                | <i>f</i>       | <i>l</i>                   | <i>f</i>               | <i>f</i>   |
| <i>j</i> 310           | —                | —              | —                          | —                      | <i>j</i> * |
| <i>M</i> 1 $\bar{1}$ 0 | <i>b</i>         | <i>m</i>       | <i>b</i>                   | <i>b</i>               | <i>M</i>   |
| <i>h</i> 1 $\bar{2}$ 0 | <i>h</i>         | <i>h</i>       | <i>q</i>                   | <i>h</i>               | <i>h</i>   |
| <i>y</i> 025           | —                | —              | <i>y</i>                   | <i>y</i>               | —          |
| <i>x</i> 035           | —                | —              | <i>x</i>                   | <i>x</i>               | —          |
| <i>d</i> 011           | <i>d</i>         | <i>d</i>       | <i>d</i>                   | <i>d</i>               | <i>d</i>   |
| <i>n</i> 0 $\bar{1}$ 1 | —                | —              | <i>n</i>                   | <i>n</i>               | <i>n</i>   |
| <i>r</i> 101           | —                | —              | —                          | <i>r</i>               | <i>r</i>   |
| <i>q</i> 1 $\bar{0}$ 1 | —                | —              | —                          | <i>q</i>               | <i>q</i>   |
| <i>e</i> 1 $\bar{1}$ 1 | —                | —              | —                          | —                      | <i>e</i> * |
| <i>s</i> 1 $\bar{1}$ 1 | <i>s</i>         | <i>b</i>       | <i>s</i>                   | <i>s</i>               | <i>s</i>   |
| <i>o</i> 1 $\bar{1}$ 1 | <i>o</i>         | <i>a</i>       | <i>o</i>                   | <i>o</i>               | <i>o</i>   |
| <i>w</i> 225           | —                | —              | <i>w</i>                   | <i>w</i>               | —          |
| <i>v</i> 335           | —                | —              | <i>v</i>                   | <i>v</i>               | —          |
| <i>u</i> 554           | —                | —              | <i>u</i>                   | <i>u</i>               | —          |
| <i>i</i> 1 $\bar{2}$ 2 | —                | —              | <i>i</i>                   | <i>i</i>               | —          |
| <i>t</i> 122           | —                | —              | <i>t</i>                   | <i>t</i>               | —          |
| <i>k</i> 1 $\bar{2}$ 1 | —                | —              | —                          | —                      | <i>k</i> * |
| <i>p</i> 1 $\bar{2}$ 1 | —                | —              | <i>p</i>                   | <i>p</i>               | <i>p</i>   |

pass light, but not so small as to prevent reliable measurements on the traces of a sufficient number of the crystal planes. The optical data obtained are summarized in Table 5, in which the co-ordinate angles for the ellipsoid axes refer to the same pole and prime meridian as that used for the crystal faces. The optical orientation and the positions of the

optic axes are represented stereographically in figure 6. There is no pseudo-symmetry in the orientation, which is in keeping with the lack of pseudo-symmetry in the crystal lattice and the absence of twinning

TABLE 4. BABINGTONITE—Ca<sub>2</sub>Fe''Fe'''Si<sub>5</sub>O<sub>14</sub>(OH)

Triclinic; pinacoidal— $\bar{1}$

$a:b:c=0.6417:1:0.5746$ ;  $\alpha=91^{\circ}31'$ ,  $\beta=93^{\circ}51'$ ,  $\gamma=104^{\circ}04'$   
 $p_0:q_0:r_0=0.9227:0.5910:1$ ;  $\lambda=87^{\circ}28\frac{1}{2}'$ ,  $\mu=85^{\circ}39'$ ,  $\nu=75^{\circ}49\frac{1}{2}'$   
 $p_0'=0.9257$ ,  $q_0'=0.5929$ ;  $x_0'=0.0673$ ,  $y_0'=0.0443$

| Forms                       | $\phi$   | $\rho$ | $A$     | $B$     | $C$    |
|-----------------------------|----------|--------|---------|---------|--------|
| <i>c</i> 001                | 56°39½'  | 4°36½' | 85°39'  | 87°28½' | 0°00'  |
| <i>b</i> 010                | 0 00     | 90 00  | 75 49½  | 0 00    | 87 28½ |
| <i>a</i> 100                | 75 49½   | 90 00  | 0 00    | 75 49½  | 85 39  |
| <i>m</i> 110                | 47 36    | 90 00  | 28 13½  | 47 36   | 85 27  |
| <i>f</i> 210                | 59 46    | 90 00  | 16 03½  | 59 46   | 85 24  |
| <i>j</i> 310                | 64 42    | 90 00  | 11 07½  | 64 42   | 85 26½ |
| <i>M</i> 1 $\bar{1}$ 0      | 112 11½  | 90 00  | 36 32   | 112 11½ | 87 24½ |
| <i>h</i> 120                | 136 54   | 90 00  | 61 04½  | 136 54  | 89 13  |
| <i>y</i> 025                | 13 27    | 16 08½ | 82 35½  | 74 19   | 13 09½ |
| <i>x</i> 035                | 9 33     | 22 05  | 81 18   | 68 14½  | 19 14  |
| <i>d</i> 011                | 6 02½    | 32 39  | 79 15½  | 57 33½  | 29 55  |
| <i>n</i> 0 $\bar{1}$ 1      | 173 00½  | 28 56  | 93 28   | 118 41½ | 31 13½ |
| <i>r</i> 101                | 74 19    | 45 03½ | 44 57½  | 78 58   | 40 41½ |
| <i>q</i> $\bar{1}$ 01       | -102 23½ | 40 22  | 130 21  | 97 59   | 44 41½ |
| <i>e</i> $\bar{1}\bar{1}$ 1 | -133 02½ | 48 38½ | 131 06  | 120 49  | 53 11  |
| <i>s</i> 1 $\bar{1}$ 1      | 108 27   | 45 29  | 53 05½  | 103 02½ | 42 45½ |
| <i>w</i> 225                | -56 49   | 19 13  | 102 53  | 79 37½  | 31 37½ |
| <i>v</i> 335                | -60 44½  | 28 22½ | 111 11½ | 76 34   | 30 45  |
| <i>o</i> $\bar{1}$ 11       | -63 41½  | 42 48½ | 121 07  | 72 28½  | 45 16½ |
| <i>u</i> 554                | -64 32½  | 49 26  | 125 48½ | 70 56½  | 51 55½ |
| <i>i</i> 122                | 130 08½  | 34 01½ | 70 57½  | 111 09  | 32 58½ |
| <i>t</i> $\bar{1}$ 22       | -36 04   | 32 56½ | 101 42  | 63 55½  | 33 26½ |
| <i>h</i> $\bar{1}$ 21       | -148 45  | 58 00  | 127 10  | 136 28  | 62 11  |
| <i>p</i> $\bar{1}$ 21       | -39 36½  | 52 29  | 109 50½ | 52 20   | 53 07½ |

in babingtonite. For comparison with the new orientation we give the orientation obtained on crystals from Arendal, Norway, by Washington & Merwin (1923), transformed to the adopted crystal setting. The agree-

ment in these independently determined orientations is satisfactory and is in accord with the noteworthy constancy in the chemical composition of the species.

TABLE 5. BABINGTONITE: OPTICAL ELEMENTS

|                | Washington<br>& Merwin |        |        |        |                |           |  |
|----------------|------------------------|--------|--------|--------|----------------|-----------|--|
|                | $\phi$                 | $\rho$ | $\phi$ | $\rho$ | $n(\text{Na})$ |           |  |
| X (dark green) | -104°                  | 46°    | -104°  | 44°    | 1.720          | } ± 0.003 | Positive<br>2V = 76 ± 2°<br>r > v strong |
| Y (lilac)      | 145                    | 70     | 145    | 71     | 1.731          |           |  |
| Z (brown)      | 39                     | 51     | 40     | 53     | 1.753          |           |  |

None of the principal optical directions is nearly normal to a prominent form. An optic axis can, however, always be seen inclined at 10° to the normal to the basal cleavage.

*Structural lattice.* The structural lattice of babingtonite was determined on a small crystal from Woburn, by a method which is entirely independent of the known morphology. Rotation and equator Weissenberg photographs were taken with copper radiation about three zone-axes, giving values for three non-coplanar lattice periods, three pairs of values for the spacings of the provisional axial planes, and three accurately measurable values for the reciprocal axial angles. A study of the lattice parameters thus obtained showed that the three chosen axes of rotation,

TABLE 6. BABINGTONITE: STRUCTURAL LATTICE CONSTANTS

| From rotation<br>photographs | From Weissenberg photographs |                |                           |               |                          |
|------------------------------|------------------------------|----------------|---------------------------|---------------|--------------------------|
|                              | $\text{\AA}$                 | $\text{\AA}$   | $\text{\AA}$              | $\text{\AA}$  | $\text{\AA}$             |
| $a_0 = 7.36$                 | $d_{100} = 7.16$             | $a^* = 0.2150$ | $\alpha^* = 87^\circ 12'$ | $a_0 = 7.39$  | $\alpha = 91^\circ 48'$  |
| $b_0 = 11.52$                | $d_{010} = 11.18$            | $b^* = 0.1377$ | $\beta^* = 85^\circ 39'$  | $b_0 = 11.52$ | $\beta = 93^\circ 48'$   |
| $c_0 = 6.58$                 | $d_{001} = 6.60$             | $c^* = 0.2332$ | $\gamma^* = 75^\circ 56'$ | $c_0 = 6.61$  | $\gamma = 103^\circ 54'$ |

which were the previously chosen crystallographic axes, were also the directions of three shortest non-coplanar lattice periods. The lattice constants measured and computed from the x-ray photographs are given in Table 6.

The above structural cell elements refer to the unique orientation fixed by the previously stated morphological conventions. The direct lattice elements obtained from the Weissenberg photographs give the following ratio, which agrees well with the previously determined geometrical elements:

$$a_0:b_0:c_0=0.642:1:0.574; \alpha=91^\circ48', \beta=93^\circ48', \gamma=103^\circ54'$$

$$a:b:c=0.6411:1:0.5747; \alpha=91^\circ28', \beta=94^\circ12', \gamma=104^\circ11'.$$

This agreement shows that the geometrical equivalent of the structural lattice was correctly discerned in the gnomonic projection of the external planes. It will be observed that the shortest cell-edge is the vertical axis  $c[001]$ , the longest cell-edge is the lateral axis  $b[010]$ . This relation generally obtains when a simple triclinic lattice cell is oriented according to morphological conventions; and it might well form the basis of a rule for orienting triclinic cells in cases of poor or variable crystal development.

*Structural lattice of Gossner & Mussgnug.* These authors (1928) determined the structural lattice of a crystal of babingtonite from Arendal, by measuring the identity periods in several lattice rows whose angular relations were known from the geometrical crystallography. The setting of Gossner & Mussgnug is related to the normal setting by the transformation, Gossner & Mussgnug to Richmond:  $010/0\bar{1}\bar{1}/\bar{1}00$ . The relation of their unit cell to ours is shown in figure 5 which gives two cells of the normal setting (elements:  $a b c \alpha \beta \gamma$ ) in full lines, and one cell of Gossner & Mussgnug (elements:  $a' b' c' \alpha' \beta' \gamma'$ ) in dotted lines. Corresponding identity periods in the structural lattices compare as follows:

## Gossner &amp; Mussgnug

$$a[\bar{1}00]=6.73\text{\AA}$$

$$b[010]=7.54$$

$$[0\bar{1}\bar{1}]=11.83 \text{ (calc.)}$$

$$c[001]=12.43$$

## Richmond

$$c[001]=6.61\text{\AA}$$

$$a[100]=7.39$$

$$b[010]=11.52$$

$$[\bar{1}10]=12.10 \text{ (calc.)}$$

Apart from a systematic difference of about three per cent in the two sets of values, due perhaps to differences in materials and methods, the agreement is good. The four periods are the four shortest non-coplanar periods in the structural lattice. Both sets of values show that the vertical period of Gossner & Mussgnug,  $c[001]$ , is the fourth-shortest period, and is therefore improperly chosen according to the structural convention which Gossner clearly recognizes and often emphasizes.

*Content of the unit cell.* Five superior analyses of babingtonite are given by Palache & Gonyer (1932), four from localities in Massachusetts (by Gonyer) and one from Arendal, the type locality (by Washington). From these analyses, which show little variation, Palache and Gonyer deduce the empirical formula:  $\text{Ca}_2\text{Fe}''\text{Fe}'''\text{Si}_5\text{O}_{14}(\text{OH})$ , which accepts hydroxyl as essential, neglects the small reported amounts of Ti, Al, Mn, Mg, Na+K, and agrees well with the found proportions of the main constituents. From the cell determination of Gossner & Mussgnug (1928)



Palache and Gonyer found that the unit cell of babingtonite contains two of the above empirical molecules. Since this cell content widely differs from that proposed by Gossner & Mussgnug it is desirable to make a count of the atoms of the unit cell, using the new cell elements together with the available analyses and corresponding density values.

The volume of the unit cell of babingtonite is  $V_0 = a_0 b_0 c_0 / (1 - \cos^2 \alpha - \cos^2 \beta - \cos^2 \gamma - 2 \cos \alpha \cdot \cos \beta \cdot \cos \gamma) = 545$  cubic Å. The molecular weight of the unit cell is  $M_0 = Vd/A = 1112$ , which varies slightly with the measured densities. From the given percentage weight of an oxide in an analysis in which the values are reduced to the sum of 100, the number of atoms of an element in the unit cell is  $N = mM_0n/100$ , where  $m$  is the molecular proportion of the oxide containing the element, and  $n$  is the number of atoms of the element in the oxide. Table 7 gives the values of

TABLE 7. BABINGTONITE: CONTENT OF THE UNIT CELL

| Analysis | 1        | 2        | 3        | 4        | 5        |
|----------|----------|----------|----------|----------|----------|
| Density  | 3.368    | 3.369    | 3.340    | 3.342    | 3.359    |
|          | <i>N</i> | <i>N</i> | <i>N</i> | <i>N</i> | <i>N</i> |
| Si       | 9.73     | 9.73     | 9.65     | 9.59     | 9.79     |
| Al       | 0.04     | 0.04     | —        | 0.02     | 0.18     |
| Ti       | —        | —        | —        | 0.04     | 0.04     |
| Fe'''    | 2.04     | 2.02     | 2.02     | 1.88     | 1.86     |
| Fe''     | 1.45     | 1.57     | 1.56     | 1.66     | 1.19     |
| Mn       | 0.19     | 0.17     | 0.18     | 0.12     | 0.31     |
| Mg       | 0.27     | 0.18     | 0.13     | 0.17     | 0.26     |
| Ca       | 3.92     | 3.91     | 3.90     | 4.00     | 3.68     |
| Na+K     | 0.04     | 0.01     | 0.06     | 0.02     | 0.14     |
| H        | 1.50     | 1.58     | 1.52     | 1.64     | 1.14     |
| Oxygen   | 29.18    | 29.18    | 28.89    | 28.89    | 28.80    |

1. Winchester Highlands (Woburn), Mass.; anal. Gonyer.
2. Holyoke, Mass.; anal. Gonyer.
3. Deerfield, Mass.; anal. Gonyer.
4. Somerville, Mass.; anal. Gonyer. Analyses 1-4 in Palache & Gonyer (1932).
5. Arendal, Norway; anal. Washington in Washington & Merwin (1923).

*N* obtained in this way from the five analyses of babingtonite, which are numbered as in Palache & Gonyer (1932).

Allowing a systematic increase of about three per cent in values of *N*, neglecting Al, Ti, Na+K, as unessential, and taking the H number as 2, babingtonite contains thirty atoms of oxygen in the unit cell, and the cell formula is:



in which  $\text{Fe}'''$  may be associated with small amounts of Ti;  $\text{Fe}''$  with Mn and Mg; Ca with Na and K. This confirms the formula of Palache & Gonyer and disproves that of Gossner & Mussgnug (1928), namely  $4[\text{Si}_2\text{O}_6\text{Ca Fe SiO}_2]$ , which does not represent the number of atoms in the unit cell or their proportions, and omits essential constituents.

*Systematic relations.* In the systematic mineralogies babingtonite follows rhodonite in the so-called triclinic section of the pyroxene group. The two minerals have similar geometrical elements, which is surprising in view of their apparently dissimilar compositions. Structural studies have shown that the pyroxene group is naturally limited to those species that have the structure of diopside; and thus the triclinic section of the pyroxene group has become a discredited misnomer.

Recently babingtonite has been variously classified: Gossner (1928) regards babingtonite as related to anorthite and epididymite; Palache & Gonyer (1932) concluded that babingtonite belongs in no existing group; Berman (1937) places babingtonite in a group of "miscellaneous pyroxenoids."

From the existing structural data on the two species we find that their geometrical similarity actually expresses near equality of the absolute lattice parameters; and that the cell contents show a relation that would not be suspected from the empirical formulas. These relations appear when we take the structural cell of babingtonite, in the second setting of Gossner & Mussgnug (1928, p. 279), turn it  $180^\circ$  about the vertical axis, and compare the resulting lattice parameters with those given for rhodonite by Gossner & Brückl (1928). Appending the two cell contents, as given by the cell volumes and densities, we have the following comparison:

| BABINGTONITE  | RHODONITE   |
|---|---|
| $a_0=7.54, b_0=12.43, c_0=6.73$   | $a_0=7.77, b_0=12.45, c_0=6.74$                                 |
| $\alpha=86^\circ 12', \beta=93^\circ 51', \gamma=112^\circ 22'$                       | $\alpha=85^\circ 10', \beta=94^\circ 04', \gamma=111^\circ 29'$ |
| $\text{Fe}_2''' \text{Fe}_2'' \text{Ca}_4 \text{Si}_{10} \text{O}_{28} (\text{OH})_2$ | $(\text{Mn, Fe, Ca})_{10} \text{Si}_{10} \text{O}_{30}$         |

Although the above lattice parameters do not correspond to the normal setting, they do represent unit cells of the respective structural lattices; and since all unit cells of a simple lattice have the same volume the above comparison is valid. Such agreement in all of the six triclinic lattice parameters points to a close structural similarity in the two species. If we express the two cell contents as  $10 \text{RSiO}_3$ , then babingtonite appears to have a rhodonite structure, with two oxygen positions occupied by hydroxyl and two cation positions unoccupied. Since the powder photographs of the two minerals, illustrated in figure 7, do not apparently show such close structural similarity, the above argument can only be tentatively accepted. An investigation of rhodonite must

be made, similar to that presented in this paper, before the validity of our argument can be admitted.

Rhodonite and babingtonite show only a partial relation to the triclinic wollastonite group of Peacock (1935), whose general cell content is  $6 \text{RSiO}_3$ . Without entering into details it may be said that the structural relation between rhodonite and wollastonite is confined to near equality of two of the principal lattice periods and the included axial angle; the remaining lattice parameters are quite dissimilar. This points to a similarity only in the ground plan of the two structures. We conclude therefore, that babingtonite should accompany rhodonite in one group of the pyroxenoids of Berman, while the wollastonite group forms another group in the same family.

*Summary.* Excellent crystals of babingtonite from Woburn, Massachusetts, are triclinic:  $a:b:c=0.6417:1:0.5746$ ;  $\alpha=91^\circ 31'$ ,  $\beta=93^\circ 51'$ ,  $\gamma=104^\circ 04'$  (Dauber's elements computed to the normal setting of Peacock). Fourteen known forms were observed; also the new forms  $j\{310\}$ ,  $e\{111\}$ ,  $k\{121\}$ , and the new but uncertain forms  $\{350\}$ ,  $\{121\}$ . X-ray measurements, independent of the external geometry, gave:  $a_0=7.39 \text{ \AA}$ ,  $b_0=11.52 \text{ \AA}$ ,  $c_0=6.61 \text{ \AA}$ ;  $\alpha=91^\circ 48'$ ,  $\beta=93^\circ 48'$ ,  $\gamma=103^\circ 54'$ ;  $a_0:b_0:c_0=0.642:1:0.574$ . The agreement shows that the structural lattice was correctly inferred from the morphology. From existing analyses and densities the unit cell contains:  $\text{Fe}_2'''\text{Fe}_2''\text{Ca}_4\text{Si}_{10}\text{O}_{28}(\text{OH})_2$ . New optical data:

|                | $\phi$       | $\rho$ | $n(\text{Na})$ |   |
|----------------|--------------|--------|----------------|---|
| X (dark green) | $-104^\circ$ | 46°    | 1.720          | Positive<br>$2V=76^\circ \pm 2^\circ$<br>$r > v$ strong |
| Y (lilac)      | 145          | 70     | 1.731          |   |
| Z (brown)      | 39           | 51     | 1.753          |   |

Babingtonite and rhodonite form a group of structurally related pyroxenoids, which shows only partial relations to the wollastonite group.

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#### EXPLANATION OF THE FIGURES

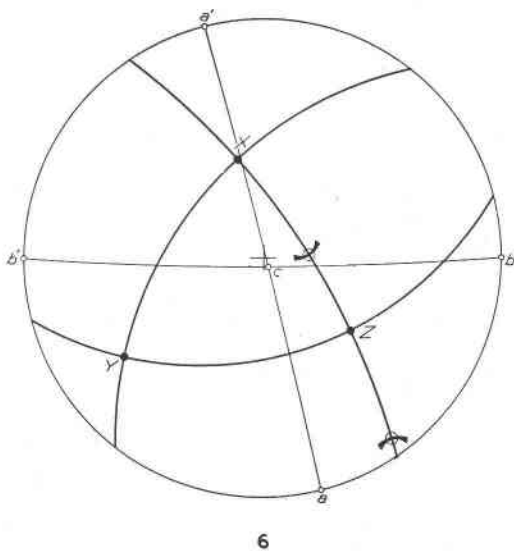
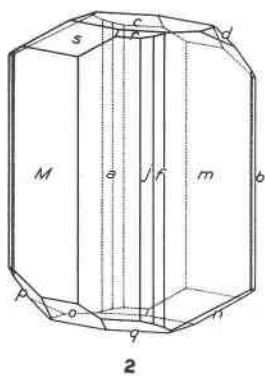
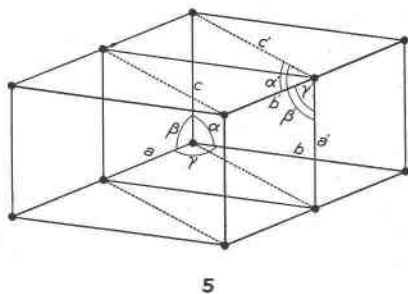
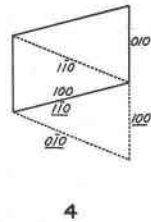
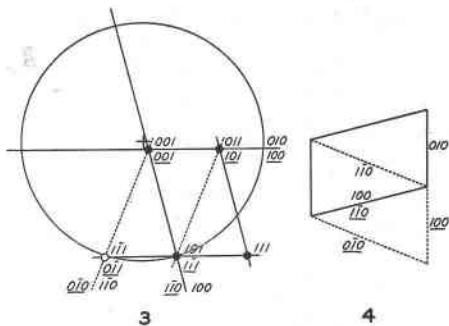
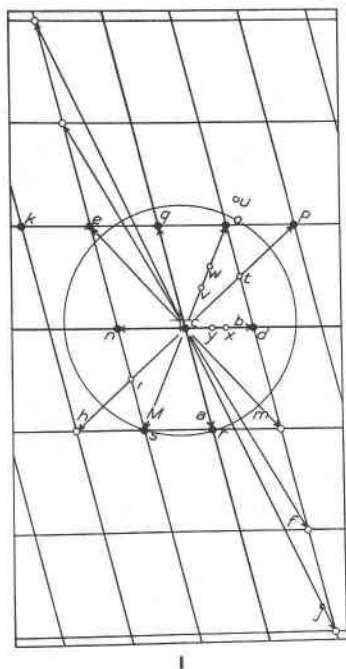
FIG. 1. Babingtonite: gnomonic projection of the known forms.

FIG. 2. Babingtonite: typical doubly terminated crystal from Woburn, Mass.

FIGS. 3, 4. Babingtonite: relation of Dauber's setting to the normal setting, in the gnomonic projection and direct lattice; dotted cells and underlined symbols are those of Dauber.

FIG. 5. Babingtonite: relation of two unit cells of babingtonite in the normal setting (full lines and unprimed elements) and one unit cell of Gossner & Musssnug (dotted lines and primed elements).

FIG. 6. Babingtonite: stereographic projection of the optical orientation and the positions of the optic axes.



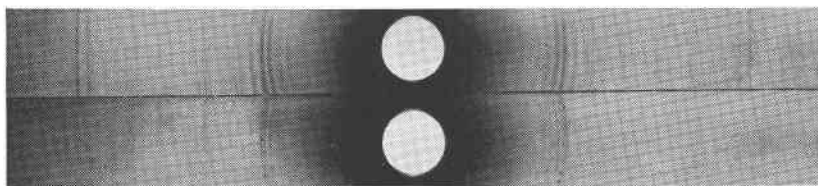


FIG. 7. Babingtonite: powder photographs of babingtonite (above) and rhodonite (below) taken with unfiltered iron radiation.

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