ON WOLLASTONITE AND PARAWOLLASTONITE.

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CONTENTS.

INTRODUCTORY.

Wollastonite rarely occurs in crystals with terminations suitable for goniometric measurement, and consequently there was considerable uncertainty among the early mineralogists concerning the identity and symmetry of this mineral. Haüy (1822, p. 438) accepted wollastonite as an independent species co-ordinate in rank with amphibole and pyroxene, and described it as orthorhombic. Phillips (1823, p. 23) showed that wollastonite has the same cleavage angle as *tabular spar* which he referred to the triclinic system. Mohs (1825, p. 286) lists wollastonite as a synonym for *prismatic augite spar* which he gives as triclinic or monoclinic. Later mineralogies retain wollastonite as a valid species and a member of the pyroxene group, and thus the name of the designer of one of the earliest types of reflecting goniometer is perpetuated in a mineral of undoubted validity and, as will appear, of unusual crystallographic interest.

The first adequate measurements of wollastonite were those of Brooke (1831) who recognized the monoclinic symmetry of the crystals from Vesuvius and chose two prominent cleavages in the orthodome zone, (100) and ($\bar{1}$02) of this paper, as base and orthopinacoid respectively. Later morphological work on wollastonite served in the main to confirm and amplify Brooke's observations. Vom Rath (1869) made a careful study of a single exceptionally fine Vesuvian crystal for which he proposed a new orientation which has been retained by later workers including the present writer. Hessenberg (1870) studied wollastonite from Santorin and Cziklova with results in full agreement with those of vom Rath. Scacchi (1889) recorded twinning on the orthopinacoid on Vesuvian crystals. Grosser (1891) proposed new elements in vom Rath's orientation, on the basis of numerous refined measurements. Zambonini (1910) failed to find twins on Scacchi's law but otherwise confirmed the previous observations.

Thus far wollastonite would seem to be a well-understood species unlikely to yield novelties from further study. But even the early work contains indications of abnormality; this appears in the early disagreement over the symmetry, the absence of the clinopinacoid[1] and the unit pyramid,[2] and in Penfield's description (in Dana, 1892, pp. 371-2) of wollastonite crystals from Diana, New York, wholly terminated by a prismatic form *h* with the unlikely symbol (540).

Still more suggestive of abnormality were Eakle's (1917) observations on wollastonite from the crystalline limestone at Crestmore, California. Of the four types of wollastonite described by Eakle the second and fourth were suitable for goniometric study. The second type was found to conform to the classical descriptions of wollastonite. In the fourth type, however, the orthodome zone agreed with that of wollastonite as previously described, but the terminations were found to be entirely different; on these Eakle found twelve new pyramids and prisms while not a single known terminal form, except *q*(340) and *h*(540) was observed. Eakle noticed that his fourth type lacked full monoclinic symmetry and might be monoclinic-hemimorphic, or triclinic. Referred to vom Rath's axes Eakle's new forms received symbols which are peculiar in that they all contain the number four.

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[1] Hessenberg wrote: "Ich glaube auch eine Spur von der Längsfläche ∞ P ∞ zu entdecken, welche sonst am Wollastonit noch nicht beobachtet worden ist" (1870, p. 35). But this doubtful observation has not been confirmed by later work.

[2] Eakle reported *p*(111) as a single rough face on one crystal, but this observation likewise lacks confirmation (1917, p. 335).

A clue to the explanation of Eakle's surprising observations was found by Warren (1931) in an X-ray study of the monoclinic pyroxenes. Using wollastonite from Chiapas, Mexico, and pectolite from Giellebekk, Norway, Warren showed that these species, hitherto grouped with the pyroxenes as a monoclinic pair, formed an isomorphous triclinic pair with a structure wholly different from that of diopside. Furthermore it was shown that wollastonite and pectolite exhibited a peculiar "pseudo-monoclinic" symmetry due to complete symmetry of the even but not the odd layer lines about the equator in 15° oscillation diagrams taken with the X-ray beam at right-angles to the axis (*b*-axis) of the prismatically developed zone. Finally Warren showed that axes corresponding to the unit cell which he deduced were obtained by taking the prism (140) on the accepted monoclinic axes of wollastonite as the pinacoid (010) in conjunction with the accepted pinacoids (100) and (001).

A study of Eakle's paper in the light of Warren's results soon showed that the unnatural symbols of the new terminal forms of Eakle's fourth type would be simplified on triclinic axes; but in the absence of a projection or adequate drawings it was not possible to discover which of the two possible faces of each of Eakle's "monoclinic" forms had been actually observed on each termination.

Is wollastonite triclinic or monoclinic? Are there two modifications of wollastonite, one triclinic and the other monoclinic? Are the crystals described as monoclinic perhaps triclinic twins? These questions could not be answered without further study. At Professor Palache's request, therefore, Professor Pabst of the University of California courteously sent the late Professor Eakle's original crystals of the fourth Crestmore type for re-study. Doctor Foshag of the United States National Museum kindly provided a limestone block from Vesuvius with wollastonite of the type often described by the early workers. For the use of these materials the writer records his indebtedness. In their study Professor Palache assisted with encouraging interest and helpful advice. Professor B. E. Warren discussed the problem and prepared further X-ray photographs that added final confirmation of the results reached by morphological and optical study. In the working out of the results, which was finished during a visit to Heidelberg in the summer of 1933, Mr. R. Schroeder of the Victor Goldschmidt Institut für Krystallforschung assisted by undertaking a share of the calculations.

MORPHOLOGY.

Measurement, discussion and presentation. The present study will show that wollastonite occurs in two closely related modifications, one triclinic and the other monoclinic. The two modifications have a common prismatically developed zone, the orthodome zone of the monoclinic modification. The relations between the two form-systems appear most clearly in projections on the plane normal to the axis of the prismatically developed zone. Such projections follow directly from the measurements on the two-circle goniometer. Both modifications of wollastonite will, therefore, be projected and discussed in second inversion (Peacock, 1934A, p. 250), in which the plane of the projection is normal to the *b*-axis.

Triclinic wollastonite from Crestmore, California. The Crestmore crystals of Eakle's fourth type (1917, pp. 336-8) are stout, colourless, transparent, singly-terminated prisms bounded by numerous brilliant faces and sharp edges in the prismatically developed zone and somewhat corroded faces and rounded edges on the terminations. The crystals are 1-3 mm. in cross-section, with some oscillatory combination of forms in the prismatically developed zone but without marked tendency to flattened development. The reflections from the faces in the principal zone are for the most part strong and sharp; the signals from the terminal faces are weaker but scarcely less sharply defined.

A plan and gnomonic projection of a typical right-hand termination (Figure 1) shows at once that these crystals are unquestionably triclinic. The filled points and the direction arrows represent the observed faces; the full lines are thus the principal zones of the crystal. These form an oblique, excentric, and, therefore, triclinic net. There is no symmetry, each terminal face representing a separate form. The blank points and broken zone-lines represent some of the known forms and zones of wollastonite according to the data in the handbooks. The triclinic and monoclinic zone-nets have exactly the same size and shape and, therefore, the projection elements, r_2, p_2, μ, and all directions in the vertical zone

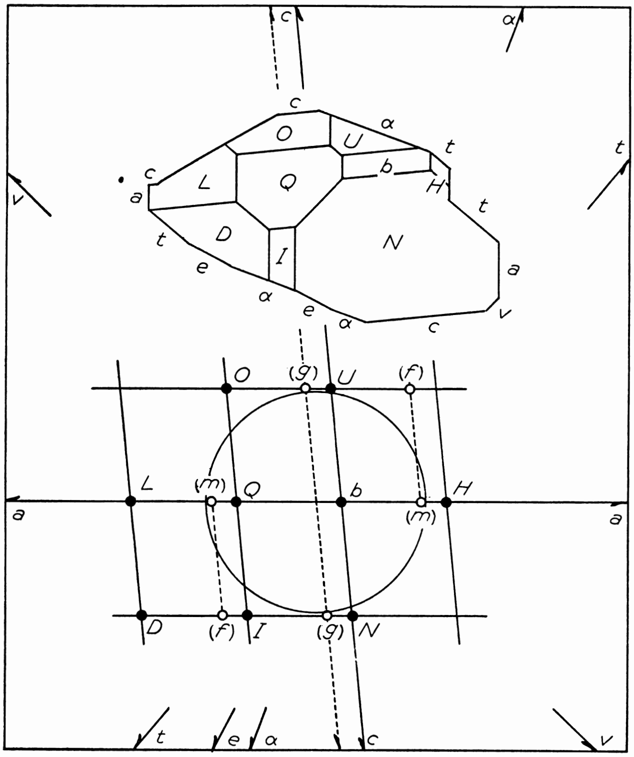

Fig. 1. Wollastonite (triclinic), Crestmore, California. Plan and gnomonic projection of a right-hand termination. The filled points and arrows are the faces observed. The blank points are common forms of monoclinic wollastonite.

are common to both. The triclinic net is laterally displaced so that $x_2 = 0$ and $y_2 = \frac{1}{4}p_2$. As far as numerous accurate measurements show, these equalities appear to be exact and, therefore, the triclinic elements represent a special case in which the *b*-axis is exactly at right angles to the *c*-axis, and the plane normal to the *b*-axis is a possible rational plane with the symbol (140).

Table I gives the forms observed on this crystal with the new triclinic symbols (*hkl*)T and the monoclinic symbols (*hkl*)M used by Eakle. The symbols in the zone [*a c*] remain unchanged while those of the remaining forms are notably simplified.

TABLE I.

Wollastonite. Forms on a triclinic crystal.

M.A.P.	*c*	*b*	*a*	*H*	*Q*	*L*	*N*	*U*	*v*	*α*	*e*	*t*	*I*	*D*	*O*
Eakle	*c*	*m*:*	*a*	*h*	*q*	*l*	*n*	*u*	*v*	*α*	–	*t*	*i*	*d*:*	*o*
(*hkl*)T ...	001	010	100	110	$\bar{1}10$	$\bar{2}10$	011	$0\bar{1}1$	101	$\bar{1}02$	$\bar{2}03$	$\bar{1}01$	$\bar{1}11$	$\bar{2}11$	$1\bar{1}1$
(*hkl*)M ...	001	140	100	540	340	740	144	$\bar{1}44$	101	$\bar{1}02$	$\bar{2}03$	$\bar{1}01$	$\bar{3}44$	$\bar{7}44$	344

* Here and elsewhere in this paper Eakle's German form letters are replaced by italic letters followed by a colon.

Twelve crystals from Crestmore were completely measured, including one by Professor Palache and one by Mr. Berman. They all proved to be triclinic individuals with either right or left-hand terminations. Table II summarizes the observations on these crystals and gives the calculated two-circle angles based on the elements which are derived later.

Of the twenty-three "monoclinic" forms found by Eakle on the Crestmore crystals of his fourth type eighteen were observed by the present writer (see Table X). Sixteen of these were found as the single faces of triclinic forms. Only two of Eakle's forms appear as pairs of symmetrical faces: $q(340)$M$=R(120)$T and $Q(\bar{1}10)$T; $u(\bar{1}44)$M$=U(0\bar{1}1)$T and $F(\bar{1}22)$T. But from the projections (Figures 10, 11) and the frequency statistics (Table II) it is clear that the two faces of each pair correspond to different triclinic forms that fall symmetrically about the centre of the projection due to the special character of the triclinic net.

Eakle's five remaining forms were not found: $\tau(104)$M, $\theta(\bar{1}04)$M, $g(011)$M, $\phi(122)$M, $\mu(\bar{1}22)$M. Since these forms are not confirmed by careful re-examination of Eakle's material, it seems necessary to exclude their triclinic equivalents from the triclinic form-list.

In addition to the forms observed by Eakle sixteen further forms were found, all new to wollastonite except *w*(102),

$s(\bar{2}01)$, $\lambda(\bar{5}01)$. The majority of the new forms are based on single observations and are retained subject to confirmation. The common forms of triclinic wollastonite are: *c*, *b*, *a*, *H*, *Q*, *L*, *U*, *v*, α, *t*, *I*, *O*. With the exception of $L(\bar{2}10)$ and $\alpha(\bar{1}02)$, the symbols of the common forms contain no number greater than one.

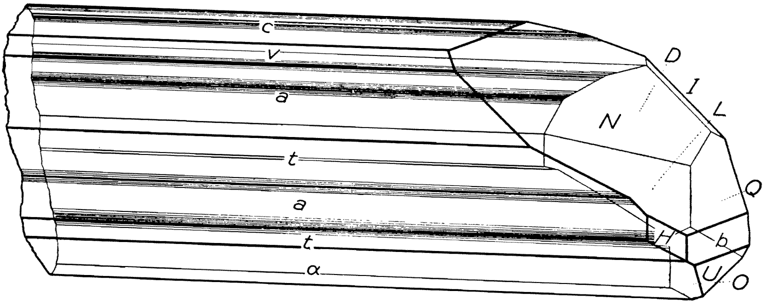

Fig. 2. Wollastonite (triclinic), Crestmore. Right-hand termination with the forms: $a(100)$, $b(010)$, $c(001)$, $H(110)$, $Q(\bar{1}10)$, $L(\bar{2}10)$, $N(011)$, $U(0\bar{1}1)$, $v(101)$, $\alpha(\bar{1}02)$, $e(\bar{2}03)$, $t(\bar{1}01)$, $I(\bar{1}11)$, $O(1\bar{1}1)$, $D(\bar{2}11)$.

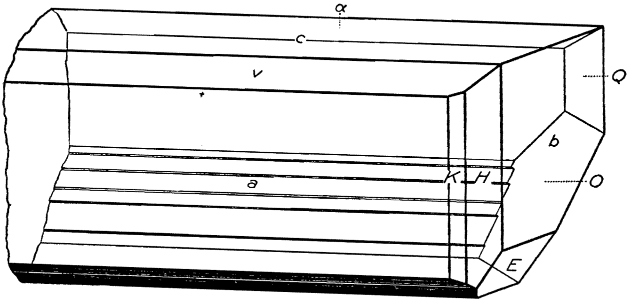

Fig. 3. Wollastonite (triclinic), Crestmore. Right-hand termination with the forms: $a(100)$, $b(010)$, $c(001)$, $H(110)$, $K(310)$, $Q(\bar{1}10)$, $E(0\bar{2}1)$, $v(101)$, $\alpha(\bar{1}02)$, $O(1\bar{1}1)$.

Figures 2-4 represent right and left-hand terminations of triclinic wollastonite from Crestmore illustrating the main variations of habit. Figure 5 gives an ideal doubly terminated crystal with all the common forms developed in about their normal relative proportions. Table III gives the combinations of forms found on the twelve measured crystals.

Triclinic wollastonite from Monte Somma. The cavities in the ejected limestone block from Monte Somma contain innumerable small crystals of wollastonite, some of which appear to be single crystals while others are clearly stocks composed of several individuals in parallel growth. A number of the smallest, apparently single crystals, were detached and measured. Ranging in cross-section from 0.3 mm. to 0.1 mm. the crystals have narrow faces in the prismatically developed zone giving good reflections, and small terminal facets in some cases so minute that their positions could be determined only approximately by adjustment to give maximum illumination.

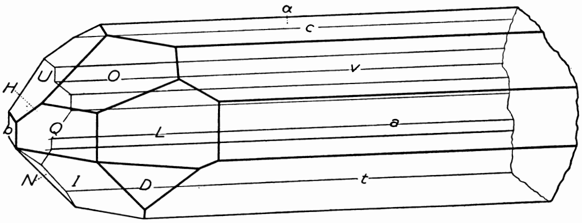

Fig. 4. Wollastonite (triclinic), Crestmore. Left-hand termination with the forms: $a(100)$, $b(010)$, $c(001)$, $H(110)$, $Q(\bar{1}10)$, $L(\bar{2}10)$, $N(011)$, $U(0\bar{1}1)$, $v(101)$, $\alpha(\bar{1}02)$, $t(\bar{1}01)$, $I(\bar{1}11)$, $D(\bar{2}11)$, $O(1\bar{1}1)$.

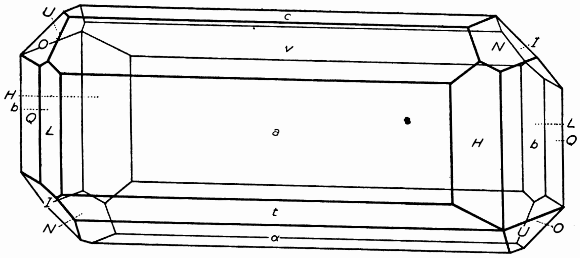

Fig. 5. Wollastonite (triclinic). Ideal crystal with the common forms: $a(100)$, $b(010)$, $c(001)$, $H(110)$, $Q(\bar{1}10)$, $L(\bar{2}10)$, $N(011)$, $U(0\bar{1}1)$, $v(101)$, $\alpha(\bar{1}02)$, $t(\bar{1}01)$, $I(\bar{1}11)$, $O(1\bar{1}1)$.

Of these small crystals seven were found to be triclinic individuals with right or left-hand terminations. This find of triclinic wollastonite in material of the type so often studied

TABLE II.

Wollastonite. Two-circle measurements on twelve triclinic crystals from Crestmore, California.

Elements of the gnomonic projection on the plane normal to the b-axis. $(h = 1)$

$x_2 = 0$
$y_2 = 0.2386$
$r_2 = 1.0410$
$p_2 = 0.9545$
$\mu = 84°35\frac{1}{2}'$

Form		Calculated		Measured mean		Measured limits		No. of Faces	No. of Crystals
		ϕ_2	ρ_2	ϕ_2	ρ_2	ϕ_2	ρ_2		
c	001	84°35½′	90°00′	84°37′	90°00′	84°29′— 84°47′	......	21	12
b	010	0 00	13 25½	0 00	13 25	......	13°13′—13°38′	12	12
a	100	0 00	90 00	0 00	90 00	......	......	24	12
R	120	0 00	35 36	0 00	35 30	......	......	1	1
H	110	0 00	50 02	0 00	50 02	......	49 53—50 07	7	7
* (*J*)	210	0 00	65 02	0 00	65 49	......	......	1	1
*(*K*)	310	0 00	72 08	0 00	72 14	......	......	1	1
*(*M*)	510	0 00	78 43	0 00	78 00	......	......	1	1
Q	$\bar{1}10$	180 00	35 36	180 00	35 31	......	35 18—35 46	8	8
L	$\bar{2}10$	180 00	59 05½	180 00	59 11	......	59 03—59 23	5	5
N	011	72 00	47 27½	71 58	47 26	71 46— 72 13	47 23—47 32	6	6
*(*S*)	012	78 09	64 43½	77 36	64 46	......	......	1	1
*(*Z*)	013	80 16½	72 24½	81 17	71 40	79 48— 82 47	71 30—71 50	2	2
(*E*)	$0\bar{2}1$	—69 53	28 52½	68 38	28 56	......	......	1	1
U	$0\bar{1}1$	—82 17	46 17	—82 12	46 20	—81 58— 82 37	46 10—46 30	8	8

* New form.
() Form requiring confirmation.

TABLE II—*Continued.*

Form		Calculated		Measured mean		Measured limits		No. of Faces	No. of Crystals
		ϕ_2	ρ_2	ϕ_2	ρ_2	ϕ_2	ρ_2		
*(*G*)	$0\bar{1}2$	—88 49½	64 14½	—89 42	63 42	......	......	1	1
(*w*)	102	60 58	90 00	63 03	90 00	......	......	1	1
v	101	44 33½	90 00	44 45	90 00	44 28 — 45 11	......	17	10
* (*u*)	605	39 48½	90 00	39 41	90 00	......	......	1	1
k	$\bar{1}03$	101 59½	90 00	102 07	90 00	......	......	1	1
* (*d*)	$\bar{2}05$	105 18½	90 00	104 40	90 00	104 21 — 104 59	......	2	2
a	$\bar{1}02$	110 05½	90 00	110 05	90 00	110 00 — 110 12	......	10	7
* *e*	$\bar{2}03$	117 36½	90 00	117 35	90 00	117 23 — 117 48	......	2	2
t	$\bar{1}01$	129 34	90 00	129 36	90 00	129 20 — 129 50	......	13	7
s	$\bar{2}01$	150 13	90 00	150 46	90 00	......	......	1	1
(λ)	$\bar{5}01$	167 30	90 00	166 47	90 00	......	......	1	1
* *l*	$\bar{6}01$	169 34	90 00	169 43	90 00	......	......	1	1
F	$\bar{1}22$	97 43	46 17	97 51	46 15	......	......	1	1
I	$\bar{1}11$	120 48	50 21	120 38	50 45	120 28 — 120 49	50 20 — 51 10	6	6
D	$\bar{2}11$	146 36½	62 02	146 46	63 01	143 38 — 149 36	62 05 — 63 59	2	2
* *V*	$\bar{3}23$	123 56	61 54½	123 53	61 54½	123 29 — 124 17	61 00 — 62 49	2	2
(*W*)	$1\bar{2}1$	—119 02½	30 39½	—115 13	30 30	......	......	1	1
* *Y*	$\bar{1}\bar{2}2$	— 59 12	50 21	— 59 12	50 24	......	......	1	1
O	$1\bar{1}1$	—128 09	52 48½	—128 08	52 43	—128 00 — 128 12	52 36 — 52 48	6	6
P	$2\bar{1}1$	—149 37½	63 59½	—149 36	63 59	......	......	1	1
* (*T*)	$\bar{2}\bar{1}2$	— 46 43½	70 38½	— 48 15	71 10	......	......	1	1

* New form.
() Form requiring confirmation.

Table III.

Wollastonite. Combinations on twelve triclinic crystals from Crestmore.

c	x	x	x	x	x	x	x	x	x	x	x	x
b	x	x	x	x	x	x	x	x	x	x	x	x
a	x	x	x	x	x	x	x	x	x	x	x	x
R	x	–	–	–	–	–	x	–	–	–	–	–
H	x	–	x	–	x	x	x	–	–	x	x	–
J	–	–	x	–	–	–	–	–	–	–	–	–
K	–	–	–	–	–	x	–	–	–	–	–	–
M	–	–	x	–	–	–	–	–	–	–	–	–
Q	x	x	x	x	x	x	–	x	–	–	x	–
L	–	–	x	–	x	–	–	x	x	–	x	–
N	x	–	–	–	x	–	x	–	–	x	x	x
S	x	–	–	–	–	–	–	–	–	–	–	–
Z	x	–	–	–	–	–	–	–	–	–	–	x
E	–	–	x	–	–	x	–	–	–	–	–	x
U	x	–	x	–	x	–	x	x	–	x	x	x
G	–	x	–	–	–	–	–	–	–	–	–	–
w	x	–	–	–	–	–	–	–	–	–	–	–
v	x	x	–	x	x	x	x	x	x	x	x	–
u	x	–	–	–	–	–	–	–	–	–	–	–
k	–	x	–	–	–	–	–	–	–	–	–	–
d	x	–	–	–	–	–	–	–	–	–	–	x
α	–	–	–	–	x	–	x	x	x	x	x	–
e	–	–	–	–	x	–	–	–	–	–	x	–
t	x	x	–	x	x	–	x	–	x	–	x	–
s	x	–	–	–	–	–	–	–	–	–	–	–
λ	x	–	–	–	–	–	–	–	–	–	–	–
l	–	–	–	–	–	–	–	x	–	–	–	–
F	–	–	–	–	–	–	–	–	x	–	–	–
I	–	x	–	x	x	–	–	x	–	–	x	x
D	–	–	–	–	x	–	–	x	–	–	x	–
V	–	x	–	–	–	–	–	x	–	–	–	–
W	–	–	–	–	–	–	–	x	–	–	–	–
Y	–	–	–	–	–	–	–	–	x	–	–	–
O	x	–	–	x	x	x	–	x	–	–	x	–
P	–	–	–	–	–	–	x	–	–	–	–	–
T	–	–	x	–	–	–	–	–	x	–	–	–

in the past was unexpected but not difficult to understand. Such crystals could hardly have been successfully measured on a single-circle instrument.

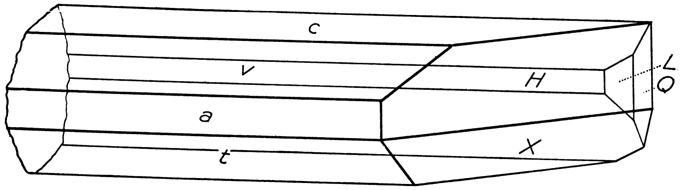

Fig. 6. Wollastonite (triclinic), Monte Somma, Italy. Right-hand termination with the forms: $a(100)$, $c(001)$, $H(110)$, $Q(\bar{1}10)$, $L(\bar{2}10)$, $X(\bar{1}\bar{1}1)$. $X(\bar{1}\bar{1}1)$ was found only at Monte Somma.

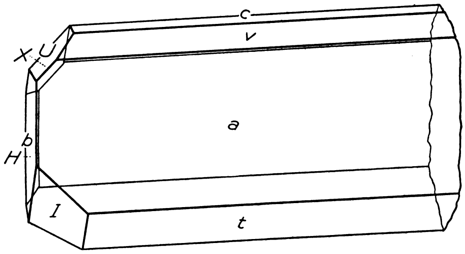

Fig. 7. Wollastonite (triclinic), Monte Somma. Left-hand termination with the forms: $a(100)$, $b(010)$, $c(001)$, $H(110)$, $U(011)$, $X(\bar{1}\bar{1}1)$, $I(\bar{1}11)$.

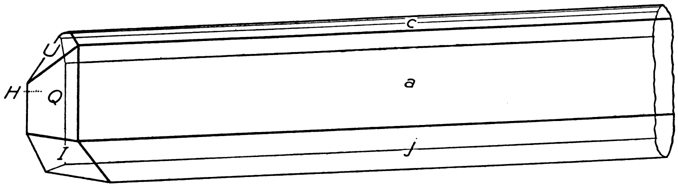

Fig. 8. Wollastonite (triclinic), Monte Somma. Left-hand termination with the forms: $a(100)$, $c(001)$, $H(110)$, $Q(\bar{1}10)$, $\alpha(\bar{1}02)$, $t(\bar{1}01)$, $j(\bar{4}01)$, $U(011)$, $I(\bar{1}11)$. $j(\bar{4}01)$ was found only at Monte Somma.

The triclinic crystals from Monte Somma are simpler than the larger Crestmore crystals, and with the exception of the new forms $j(\bar{4}01)$ and $X(\bar{1}\bar{1}1)$ observed twice and four times respectively, the forms are among those already observed on the Californian material. Table IV gives the forms observed with the calculated and measured angles, the latter including only those obtained from definite signals. Figures 6-8 illlustrate typical right and left-hand terminations.

TABLE IV.

Wollastonite. Two-circle measurements on seven triclinic crystals from Monte Somma.

Elements of the gnomonic projection on the plane normal to the *b*-axis. ($h = 1$)

$x_2 = 0$
$y_2 = 0.2386$
$r_2 = 1.0410$
$p_2 = 0.9545$
$\mu = 84°35\frac{1}{2}'$

		Calculated		Measured mean		Measured limits		No. of crystals
		ϕ_2	ρ_2	ϕ_2	ρ_2	ϕ_2	ρ_2	
c	001	84°35½′	90°00′	84°38′	90°00′	84°20′ — 85°05′	......	4
b	010	0 00	13 25½	0 00	13 45	......	......	1
a	100	0 00	90 00	0 00	90 00	......	......	4
R	120	0 00	35 36	0 00	36 30	......	......	1
H	110	0 00	50 02	0 00	50 05	......	49°50′— 50°06′	6
Q	$\bar{1}10$	180 00	35 36	180 00	35 57	......	35 15 — 36 30	6
L	$\bar{2}10$	180 00	59 05½	180 00	58 52	......	58 43 — 59 15	4
U	011	—82 17	46 17	—82 26	46 15½	......	46 15 — 46 16	2
v	101	44 33½	90 00	44 47	90 00	44 20 — 45 17	......	4
α	$\bar{1}02$	110 05½	90 00	110 38½	90 00	110 27 —110 50	......	2
t	$\bar{1}01$	129 34	90 00	130 46	90 00	129 10 —130 32	......	3
**j*	$\bar{4}01$	164 25	90 00	164 39	90 00	......	......	2
**X*	$\bar{1}\bar{1}1$	—43 25½	56 26½	—43 36	56 37	—43 25½ — 43 47	56 22 — 56 34	4
I	$\bar{1}11$	120 48	50 21	120 57	50 39	120 29 —121 40	50 21 — 51 05	4
D	$\bar{2}11$	146 36½	62 02	146 17	62 00	......	......	1

* New form.

Monoclinic wollastonite from Monte Somma. The majority of the crystals examined proved to be monoclinic individuals or composites in parallel growth on the orthopinacoid. Figure 9 gives a plan and gnomonic projection of a typical composite with left-hand terminations. The filled points and arrows are the projection points of the observed faces and the full lines are the principal zones. These form an oblique net symmetrical about the centre, which is thus the axis of symmetry of a monoclinic arrangement of faces. The blank points and broken zone-lines give some common forms and zones of triclinic wollastonite. The relations are the converse to those in Figure 1, and again the projection elements, r_2, p_2, μ, are common to both nets. In spite of the re-entrants on the crystal, the composite is not a twin but two parallel monoclinic individuals in contact on $a(100)$. No twinning operation will produce the monoclinic forms from the triclinic forms.

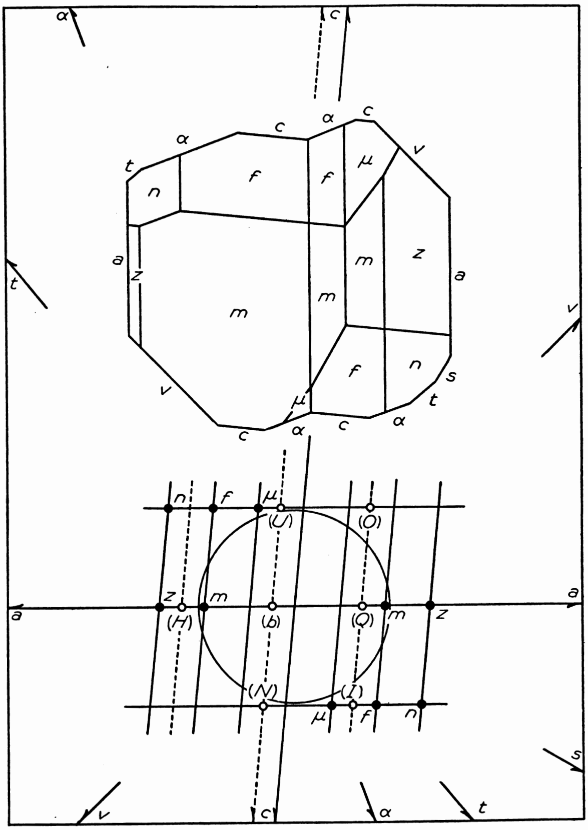

Fig. 9. Parawollastonite (monoclinic), Monte Somma. Plan and gnomonic projection of a left-hand termination of two individuals in parallel growth on $a(100)$. The filled points and arrows are the faces observed. The blank points are common forms on triclinic wollastonite. Forms: $a(100)$, $c(001)$, $m(110)$, $z(320)$, $v(101)$, $\alpha(\bar{1}02)$, $t(\bar{1}01)$, $s(\bar{1}01)$, $r(\bar{1}01)$, $\mu(\bar{1}22)$, $f(\bar{1}11)$, $n(\bar{1}22)$.

The monoclinic crystals studied are evidently of poorer quality than the best of those described in the past; but Table V, which gives the better measurements obtained from six crystals, shows most of the forms known from Vesuvius in fairly good position. And thus, apart from the rather deceptive idealization of the early drawings, the existing descriptions of the monoclinic wollastonite are undoubtedly correct. The mineral is monoclinic and holohedral, as shown by the doubly terminated tablets adhering to some of the stocks of parallel tablets, and not related to triclinic wollastonite by twinning.[3]

TABLE V.

Wollastonite. Two-circle measurements on six monoclinic crystals from Monte Somma.

Elements of the gnomonic projection on the plane normal to the *b*-axis. ($h = 1$)

$r_2 = 1.0410$
$p_2 = 0.9545$
$\mu = 84°35\frac{1}{2}'$

		Calculated		Measured mean		Measured limits		No. of faces
		ϕ_2	ρ_2	ϕ_2	ρ_2	ϕ_2	ρ_2	
c	001	84°35½′	90°00′	84°35′	90°00′	84°06′— 85°00′	......	6
a	100	0 00	90 00	0 00	90 00	......	......	7
x	120	0 00	25 31	0 00	24 40	......	24°00′—25°20′	3
m	110	0 00	43 40	0 00	44 03	......	43 18—44 30	5
z	320	0 00	55 04	0 00	55 06	......	55 02—55 11	9
g	011	84 35½	46 09	84 22	45 59½	......	45 59—46 00	2
v	101	44 33½	90 00	44 37	90 00	44 15— 44 45	......	5
w	102	60 58	90 00	61 53	90 00	......	......	1
α	$\bar{1}02$	110 05½	90 00	110 09	90 00	109 40—110 27	......	3
t	$\bar{1}01$	129 34	90 00	129 49	90 00	129 03—130 26	......	5
s	$\bar{2}01$	150 13	90 00	149 14	90 00	......	......	1
r	$\bar{3}01$	159 27½	90 00	160 20	90 00	......	......	1
i	$\bar{1}\bar{1}.0.2$	168 37½	90 00	168 25	90 00	168 00—168 50	......	2
μ	$\bar{1}22$	110 05½	47 49	110 15	47 42	110 03—110 36	46 56—48 30	8
f	$\bar{1}11$	129 34	53 21½	129 29	53 14	129 16—129 51	52 54—53 45	8
n	$\bar{3}22$	142 09	59 22½	142 15	59 12	142 08—142 22	58 55—59 26	7

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[3] While this is strictly true in the sense that a crystal of monoclinic wollastonite cannot be explained as a twin crystal of triclinic wollastonite, Doctor Max Barnick, of the Kaiser Wilhelm-Institut für Silikatforschung has found that a unit cell of monoclinic wollastonite results from two unit cells of triclinic wolastonite in twin relation about [010] (*personal communication*).

Two of the Monte Somma aggregates proved to be composites of monoclinic and triclinic wollastonite. One crystal showed the following forms: common forms in the prismatically developed zone, $a(100)$, $c(001)$, $v(101)$, $\alpha(\bar{1}02)$, $t(\bar{1}01)$; monoclinic forms, $m(110)$, $z(320)$, $\mu(\bar{1}22)$, $f(\bar{1}11)$, $n(\bar{3}22)$; triclinic forms, $Q(\bar{1}10)$, $L(\bar{2}10)$, $D(\bar{2}11)$. The other was found to have the same common forms; the monoclinic forms, $x(120)$, $z(320)$, $\mu(\bar{1}22)$, $f(\bar{1}11)$, $n(\bar{1}22)$; and the triclinic forms, $b(010)$, $R(120)$, $H(110)$, $Q(\bar{1}10)$, $I(\bar{1}11)$, $X(\bar{1}\bar{1}1)$. These composites have steps and re-entrant angles in the prismatically developed zone and on the terminations. The monoclinic and triclinic faces appear on different portions which appear to be in contact on the common orthopinacoid.

Elements and Tables. Whereas the Vesuvian crystals gave reflections only good enough to identify the forms with certainty, the Californian crystals yielded measurements which are probably as good as any that have been made on wollastonite. The best measurements of all the common forms on twelve Crestmore crystals give the following triclinic gnomonic projection elements referred to the b-axis as pole. For comparison the corresponding monoclinic projection elements were calculated from the linear elements of Grosser (1891) and of vom Rath (1869).

TABLE VI.

Wollastonite. Projection elements.

	Crestmore (M. A. P.) Triclinic	Vesuvius (Grosser) Monoclinic	Vesuvius (vom Rath) Monoclinic
x_2	0	0	0
y_2	0.2384	0	0
r_2	1.0416	1.0410	1.0382
p_2	0.9536	0.9545	0.9542
μ	84°37′	84°35½′	84°30′

Except for the quantity y_2 in the triclinic elements, which represents the excentricity of the pole $b(010)$ on the gnomonic projection and exactly equals ¼p_2, the Crestmore elements are as close to those based on Vesuvian crystals as the two sets of Vesuvian elements are to one another. There is thus no doubt that the quantities r_2, p_2, μ, are common to the triclinic and monoclinic elements. The new elements differ from those of Grosser by so slight an amount that a change is unwarranted. For the monoclinic angle-table Grosser's elements are, therefore, used; for the triclinic angle-table Grosser's elements with $y_2 = \frac{1}{4} p_2 = 0.2386$. Our monoclinic angle-table is thus in exact accord with Grosser's list of interfacial angles (1891, pp. 608-11) while the triclinic angle-table expresses the strict rational relations between the two types of wollastonite.

The following table gives a full statement of the elements of wollastonite, the first column being the linear elements in normal position, the last column the corresponding polar elements, and the middle column the projection elements on the plane normal to the *b*-axis and at unit distance from the crystal centre.

TABLE VII.

Wollastonite. Elements of the triclinic and monoclinic types.

	Triclinic	
$a = 1.0816$	$x_2 = 0$	$p_0 = 0.9169$
$b = 1$	$y_2 = 0.2386$	$q_0 = 0.9874$
$c = 0.9649$	$r_2 = 1.0410$	$r_0 = 1$
$\alpha = 90°00'$	$p_2 = 0.9545$	$\lambda = 88°45'$
$\beta = 95\ 16$	$h = 1$	$\mu = 84\ 35\frac{1}{2}$
$\gamma = 103\ 22$	$\mu = 84°35\frac{1}{2}'$	$\nu = 76\ 34\frac{1}{2}$
	Monoclinic	
$a = 1.0524$	$r_2 = 1.0410$	$p_0 = 0.9169$
$b = 1$	$p_2 = 0.9545$	$q_0 = 0.9606$
$c = 0.9649$	$h = 1$	$r_0 = 1$
$\beta = 95°24\frac{1}{2}'$	$\mu = 84°35\frac{1}{2}'$	$\mu' = 84°35\frac{1}{2}'$

The calculated two-circle angles in Tables II, V, were obtained from the projection elements and symbols. Tables VIII, IX, give the calculated angles of the representative face of each form to each pinacoid, obtained by the expression giving the angle between any two poles whose co-ordinate angles are known. To check these calculations a gnomonic projection of the known forms was carefully made from the projection elements and symbols on a primitive circle of radius 10 cm. By means of the familiar angle-point construction and a semicircular aluminium protractor[4] of 15 cm. radius, graduated in degrees and quarters of a degree on a dividing engine for graduating goniometer circles, all the pinacoidal angles were rapidly measured. The maximum and average differ-

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[4] Constructed to the writer's specification by F. Rheinheimer (P. Stoe and Co.), Heidelberg, Germany.

ences between the calculated angles and those measured on the projection are surprisingly small:

	Difference	
	Maximum	Average
ϕ_2	16½′	7½′
ρ_2	7½	2½
A	16½	7
B	20½	6½
C	18	7

Since errors in calculation are almost as likely to be great as small, agreement to one-third of a degree between the calculated angles and those measured from a projection constructed independently of these angles, may be regarded as an adequate check on the calculations.

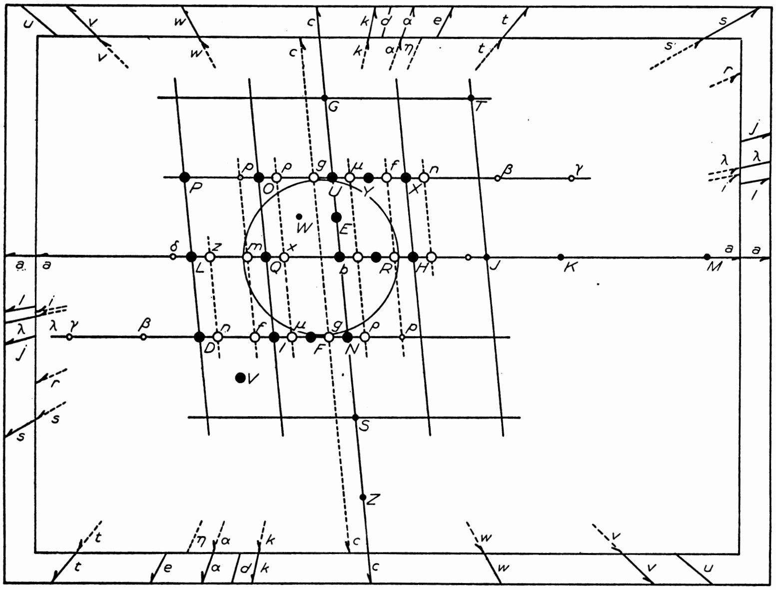

Fig. 10. Wollastonite (triclinic) and parawollastonite (monoclinic). Gnomonic projection of the known forms on the plane normal to the *b*-axis. Wollastonite: filled points and outer direction lines. Parawollastonite: blank points and inner direction lines. Confirmed forms: large points and direction lines with arrows. Forms requiring confirmation: small points and direction lines without arrows.

Table X gives the forms which have been reported on wollastonite with the letters used by several authors. The triclinic terminal forms have consistently been given capital letters to distinguish them from the monoclinic forms. The remaining changes are necessitated by the duplication of letters in the existing signatures and the desirability of avoiding German letters.

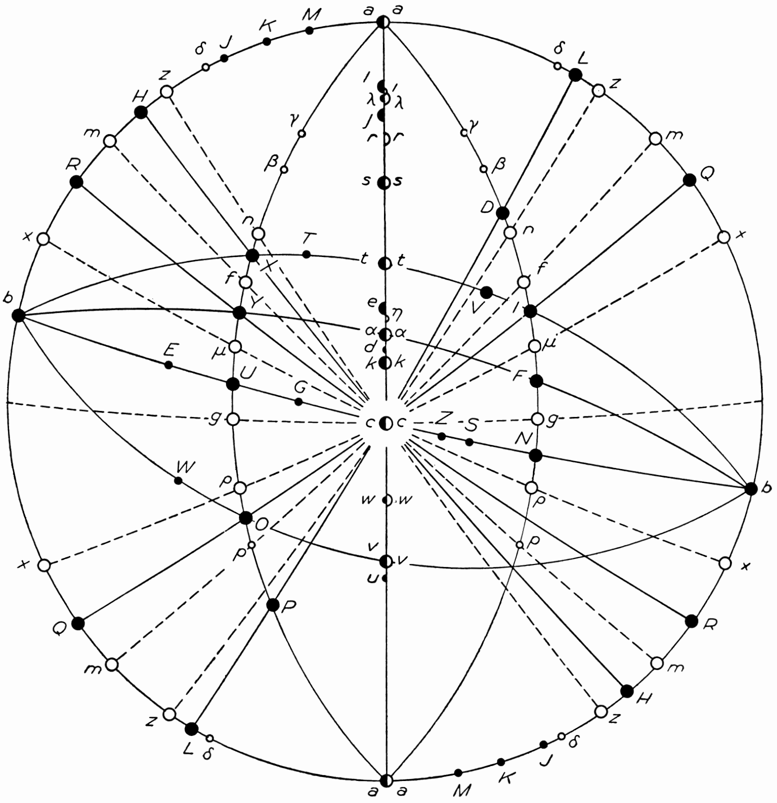

Fig. 11. Wollastonite (triclinic) and parawollastonite (monoclinic). Stereographic projection of the known forms on the plane normal to the *c*-axis. Scheme of points similar to that used in figure 12. To preserve the coincidence of the common zone [*a c*] the wollastonite (triclinic) projection has been turned about the *c*-axis to bring *a*(100) directly to the front.

Figures 10 and 11 give gnomonic and stereographic projections of the known forms of wollastonite; the former was constructed with the help of the two-circle angles on the plane normal to the *b*-axis, and the latter drawn on the plane normal

TABLE VIII.[5]

Wollastonite.

$CaO.SiO_2$ — Triclinic

$a = 1.0816$
$c = 0.9649$
$\alpha = 90°00′$
$\beta = 95\ 16$
$\gamma = 103\ 22$

$p_0 = 0.9169$
$q_0 = 0.9874$
$\lambda = 88°45′$
$\mu = 84\ 35½$
$\nu = 76\ 34½$

		A	B	C			A	B	C
a	100	0°00′	76°34½′	84°35½′	*k*	$\bar{1}03$	78°00½′	87°14′	17°24′
b	010	76 34½	0 00	88 45	*d*	$\bar{2}05$	74 41½	86 29	20 43
c	001	84 35½	88 45	0 00	*α*	$\bar{1}02$	69 54½	85 25½	25 30
R	120	54 24	22 10½	86 51½	*e*	$\bar{2}03$	62 23½	83 49½	33 01
H	110	39 58	46 36½	85 51½	*t*	$\bar{1}01$	50 26	81 30	44 58½
J	210	24 58	51 36½	85 06	*s*	$\bar{2}01$	29 47	78 22½	65 37½
K	310	17 52	58 42½	84 51	*j*	$\bar{4}01$	15 35	77 05	79 49½
M	510	11 17	65 17½	84 42	*λ*	$\bar{5}01$	12 30	76 54	82 54½
L	$\bar{2}10$	30 54½	72 31	85 21½	*l*	$\bar{6}01$	10 26	76 48½	84 58½
Q	$\bar{1}10$	54 24	49 01½	86 51½	*V*	$\bar{3}23$	60 30	69 54	46 58½
Z	013	80 44	70 39	18 05½	*T*	$\bar{2}\bar{1}2$	49 42½	61 48	51 28
S	012	79 18	62 43	26 01½	*O*	$1\bar{1}1$	60 31½	61 43½	47 55½
N	011	76 50½	44 43½	44 18	*P*	$2\bar{1}1$	39 09½	75 44	58 18
G	$0\bar{1}2$	88 56½	64 43½	26 32	*F*	$\bar{1}22$	84 26	49 29	45 15½
U	$0\bar{1}1$	84 24	45 59½	45 16	*I*	$\bar{1}11$	66 47	58 03	51 35½
E	$0\bar{2}1$	80 26½	27 05	64 10	*D*	$\bar{2}11$	42 29½	73 26½	65 31
w	102	60 58	82 32	23 37½	*Y*	$\bar{1}\bar{2}2$	66 47	44 35	51 35½
v	101	44 33½	80 29	40 02	*X*	$\bar{1}\bar{1}1$	52 45½	47 18	59 07½
u	605	39 48½	79 43½	44 47	*W*	$1\bar{2}1$	75 40½	38 48	62 09

to the *c*-axis using the angles to the pinacoids, A, B, C. The gnomonic projection connects with the orthogonal drawings; it shows particularly clearly the rational relations between the triclinic and the monoclinic form-series. The stereographic projection corresponds directly with the clinographic drawings. It brings out the remarkable insignificance of the pole 010 in the monoclinic form series; there is no face corresponding to this pole and in the projection it clearly has no importance as a zonal node.

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[5] In Tables VIII and IX the angles A, B, C are in each case angles to the nearest pinacoid *a*, *b*, *c*, respectively. The writer now prefers to give the angles to *a*(100), *b*(010), *c*(001), many of which are supplementary to those given here.

TABLE IX.[5]

Parawollastonite.

$CaO.SiO_2$ — Monoclinic

$a = 1.0524$ $p_0 = 0.9169$
$c = 0.9649$ $q_0 = 0.9606$
$\beta = 95°24½'$ $\mu = 84°35½'$

		A	B	C			A	B	C
a	100	0°00′	90°00′	84°35½	*t*	$\bar{1}01$	50°26′	90°00′	44°58½′
c	001	84 35½	90 00	0 00	*s*	$\bar{2}01$	29 47	90 00	65 37½
x	120	64 29	25 31	87 40½	*r*	$\bar{3}01$	20 32½	90 00	74 52
m	110	46 20	43 40	86 16	λ	$\bar{5}01$	12 30	90 00	82 54½
z	320	34 56	55 04	85 34	*i*	$\bar{1}\bar{1}.0.2$	11 22½	90 00	84 02
δ	210	27 39	62 21	85 12½	ρ	122	68 12½	49 51	45 33
g	011	86 06	46 09	43 51	*p*	111	53 50	55 54	50 39
w	102	60 58	90 00	23 37½	μ	$\bar{1}22$	75 15	47 49	48 01½
v	101	44 33½	90 00	40 02	*f*	$\bar{1}11$	59 15½	53 21½	55 25
k	$\bar{1}03$	78 00½	90 00	17 24	*n*	$\bar{3}22$	47 12	59 22½	62 30½
α	$\bar{1}02$	69 54½	90 00	25 30	β	$\bar{5}22$	32 11	68 17½	72 27½
η	$\bar{3}05$	65 13	90 00	30 11½	γ	$\bar{7}22$	23 56½	73 38	78 11½

Twinning. The frequently stated twinning law of wollastonite, twinning plane *a*(100), rests on somewhat inadequate observations, and consequently the law was suspected by Grosser (1891, p. 606) to be an error founded on a misinterpretation of the commonly occurring parallel growths. Twinning on *a*(100) was noticed on Vesuvian crystals by Brooke (1831, p. 191); Scacchi (1889, p. 53) also reports twins on this law and gives one drawing (Pl. II, Fig. 22) but no measurements. Spencer (in Collins, 1903, p. 359) describes and figures a twin on *a*(100) from Chiapas, Mexico, with the measured angle 10°44′ between the two (001) cleavages (calculated on our elements, 10°49′), but since the Chiapas wollastonite has been proved to be triclinic[6] by Warren and Biscoe (1931, p. 401), this otherwise valuable observation does not bear on the validity of the law in the case of the monoclinic crystals.

[6] Spencer identified with certainty *a*(100), *c*(001), *v*(101), *t*($\bar{1}01$), *r*($\bar{3}01$) and the single terminal form *q* with the monoclinic symbol (340). These forms lie in two zones whose axes intersect at exactly a right angle and thus there was no reason to doubt the monoclinic symmetry of the crystals. On the triclinic axes Spencer's forms retain their symbols unchanged with the exception of *q*, the two faces of which become R(120) and Q($\bar{1}10$). The "hemihedral development" of Spencer's second crystal is no doubt due to its triclinic character.

TABLE X.

Wollastonite. Correlation of forms and letters.

Monoclinic					Triclinic		Monoclinic					Triclinic	
	Dana (1892)	Gold-schmidt (1923)	Eakle (1917)	M. A. P.*		M. A. P.*		Dana (1892)	Gold-schmidt (1923)	Eakle (1917)	M. A. P.*		M. A. P.*
001	*c*	*u*	*c*	*c*	001	*c*	—	–	–	–	–	$\bar{4}01$	*j*
100	*a*	*c*	–	–	—	–	$\bar{5}01$	–	λ	–	–	$\bar{5}01$	λ
010	–	*b*	*a*	*a*	100	*a*	$\overline{11}.0.2$	–	*i*	–	*i*	—	–
140	–	–	*m*:	–	010	*b*	—	–	–	–	–	$\bar{6}01$	*l*
120	*x*	*x*	*x*	*x*	—	–	011	*g*	*g*	*g*	*g*	—	–
340	*q*	*l*	*q*	–	120	*R*	144	–	ζ	*n*	–	011	*N*
340	*q*	*l*	*q*	–	$\bar{1}10$	*Q*	133	–	ε	–	–	—	–
110	*m*	*e*	*m*	*m*	—	–	—	–	–	–	–	012	(*S*)
540	*h*	*k*	*h*	–	110	*H*	—	–	–	–	–	013	(*Z*)
320	*z*	*z*	*z*	*z*	—	–	$\bar{1}42$	–	–	ε	–	$0\bar{2}1$	*E*
740	–	–	*l*	–	$\bar{2}10$	*L*	$\bar{1}44$	–	–	*u*	–	$0\bar{1}1$	*U*
210	–	δ	–	(δ)	—	–	—	–	–	–	–	$0\bar{1}2$	(*G*)
—	–	–	–	–	210	(*J*)	142	–	–	ω	–	$1\bar{2}1$	(*W*)
830	*d*	*d*	–	–	—	–	111	–	–	*p*	(*p*)	—	–
—	–	–	–	–	310	(*K*)	122	ρ	*h*	φ	ρ	—	–
—	–	–	–	–	510	(*M*)	$\bar{1}44$	–	–	*u*	–	$\bar{1}22$	*F*
—	–	–	–	–	605	(*u*)	$\bar{1}22$	μ	*m*	μ	μ	—	–
101	*v*	*v*	*v*	*v*	101	*v*	$\bar{3}44$	–	–	*i*	–	$\bar{1}11$	*I*
102	*w*	*w*	–	*w*	102	(*w*)	$\bar{1}11$	*f*	*f*	–	*f*	—	–
104	–	–	τ	–	—	–	$\bar{3}22$	*n*	*n*	–	*n*	—	–
$\bar{1}04$	–	–	θ	–	—	–	$\bar{7}44$	–	–	*d*:	–	$\bar{2}11$	*D*
$\bar{1}03$	*k*	*q*	*k*	(*k*)	$\bar{1}03$	*k*	$\bar{5}22$	β	–	–	(β)	—	–
—	–	–	–	–	$\bar{2}05$	(*d*)	$\bar{7}22$	γ	–	–	(γ)	—	–
$\bar{1}02$	α	*a*	α	α	$\bar{1}02$	α	344	–	–	*o*	–	$1\bar{1}1$	*O*
$\bar{3}05$	β	α	–	(η)	—	–	744	–	–	*p*:	–	$2\bar{1}1$	*P*
—	–	–	–	–	$\bar{2}03$	*e*	—	–	–	–	–	$\bar{1}\bar{2}2$	*Y*
$\bar{1}01$	*t*	*t*	*t*	*t*	$\bar{1}01$	*t*	—	–	–	–	–	$\bar{1}\bar{1}1$	*X*
$\bar{7}05$	*l*	χ	–	–	—	–	—	–	–	–	–	$\bar{3}23$	*V*
$\bar{2}01$	*s*	*s*	*s*	*s*	$\bar{2}01$	*s*	—	–	–	–	–	$\bar{2}\bar{1}2$	(*T*)
$\bar{3}01$	*r*	*r*	–	*r*	—	–							

* In the columns headed "M. A. P." a letter indicates a confirmed form; a letter in parentheses, a form retained subject to confirmation; a dash, a form not known on one or the other modification, or rejected as insufficiently supported by measurements. Italic letters followed by a colon represent corresponding German letters.

Almost all the monoclinic aggregates examined proved to be parallel growths such as that described and illustrated in Fig. 9. One minute and imperfect composite, however, was found to have right and left-hand terminations symmetrical about the trace of *a*(100). The following table gives the calculated and measured positions of the symmetrical faces. With faces permitting only the roughest of measurements, the agreement is in some cases very poor; but together with the existing morphological evidence of twinning on *a*(100) and the frequent notices of simple and multiple twinning on this law determined optically, the present observations may serve to confirm the law for the monoclinic crystals.

TABLE XI.

Wollastonite. Measurements on a monoclinic twin on *a*(100), from Monte Somma.

		Calculated		Measured	
		ϕ_2	ρ_2	ϕ_2	ρ_2
a	$\bar{1}00$	180°00′	90°00′	182½°	90°
a	$\bar{1}00$ twin	0 00	90 00	0	90
x	$\bar{1}20$	180 00	25 31	180	22½
x	$\bar{1}20$ twin	0 00	25 31	0	24
m	$\bar{1}10$	180 00	43 40	..	..
m	$\bar{1}10$ twin	0 00	43 40	0	44½
z	$\bar{3}20$	180 00	55 04	180	55½
z	$\bar{3}20$ twin	0 00	55 04	0	55
μ	$\bar{1}22$	110 05½	47 49	111	47½
μ	$\bar{1}22$ twin	69 54½	47 49	74½	46½
f	$\bar{1}11$	129 34	53 21½	130½	53½
f	$\bar{1}11$ twin	50 26	53 21½	48	51½

It may be concluded, therefore, that monoclinic wollastonite forms twins on *a*(100) which seldom reach a sufficient size to permit goniometric measurement. Although all the triclinic crystals studied by the writer proved to be individuals, Spencer's isolated observation of twinning on *a*(100) on Chiapas wollastonite shows that the same law holds for the triclinic mineral.

Cleavage. There is considerable disagreement in the published data on the cleavage of wollastonite. Brooke (1831) gives, in our notation, ($\bar{1}02$) as the best cleavage, also (100), ($\bar{1}01$) and (001). Des Cloiseaux (1862, p. 50) gives (100),

$(\bar{1}01)$ and $\bar{1}02)$ as good cleavages and (001) as less good. Grosser (1891, p. 606) was unable to find that the cleavage after $(\bar{1}02)$ is better than the others. Dana (1892, p. 372) notes (100) and (001) as perfect cleavages, $(\bar{1}01)$ as less perfect. Spencer (in Collins, 1903, p. 359) finds perfect cleavages with (100) and (001). Zambonini (1910, p. 160) comments on the early disagreement and remarks that the cleavage after (100) is extraordinarily easy and perfect. Osborne (1931, p. 295) observes (100) and (001) as well developed cleavages, with (100) the stronger; also (101) fairly good and $(\bar{1}01)$ poor. Winchell[7] (1933, p. 402) gives (100) perfect, (001) good, $(\bar{1}01)$ and $(\bar{1}02)$ imperfect.

Some information on the cleavages of wollastonite was obtained while preparing plates for optical examination, and full data on the number and relative facility of the cleavages were gained from stout terminated crystals which had been measured on the goniometer to determine their symmetry. Such crystals were partly embedded in wax on a glass plate and cleaved in many directions with a razor blade to give prisms bounded wholly by cleavage faces.

The cleavages were found to be exactly the same in both types of wollastonite. In all, five cleavages were found in the zone [*a c*] and none transverse to the axis of this zone. In agreement with most of the earlier observations, the cohesion normal to *a*(100) proved definitely the weakest, gentle pressure producing a perfect cleavage face traversing the whole crystal parallel to *a*(100). With a well-directed blade and slightly more force, full-sized mirror-like cleavage planes were obtained parallel to α$(\bar{1}02)$, the plane which Brooke ranked as the best cleavage and used as a pinacoid. With approximately equal facility perfect cleavage faces were obtained parallel to *c*(001). Attempts to truncate the edges formed by the above three excellent cleavages gave stepped surfaces composed of the three better cleavages together with bright narrow planes parallel to *v*(101), hitherto observed only by Osborne (1931), and *t*$(\bar{1}01)$, frequently reported as a cleavage with various degrees of quality.

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[7] Winchell's diagram (Fig. 333), however, shows the traces of the cleavages after (100) and (001), and, instead of the traces of the $(\bar{1}01)$ and $(\bar{1}02)$ cleavages, traces in the directions of (201) and $\bar{2}01)$, planes which do not appear to have been mentioned as cleavages in any of the published studies on wollastonite.

TABLE XII.

Wollastonite. Measurements on cleavage prisms.

		Calculated	Measured	
			Crestmore (triclinic)	Monte Somma (monoclinic)
		ϕ_2	ϕ_2	ϕ_2
a	100	0°00′	0°00′	0°00′
a′	$\bar{1}00$	—180 00	—179 42	180 00
v	101	44 33½	44 54	44 55
v′	$\bar{1}0\bar{1}$	—135 26½	—135 25	....
c	001	84 35½	84 35	....
c′	$00\bar{1}$	— 95 24½	— 95 48	—95 25
α	$\bar{1}02$	110 05½	110 08	110 33
α′	$10\bar{2}$	— 69 54½	— 69 48	—69 49
t	$\bar{1}01$	129 34	129 22	129 38
t′	$10\bar{1}$	— 50 26	— 50 56	—50 05

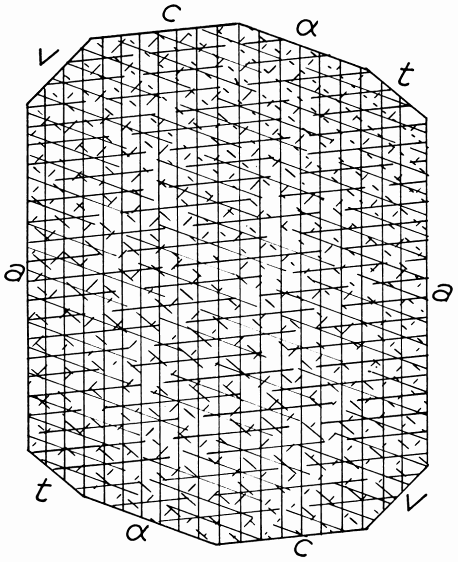

Fig. 12. Wollastonite and parawollastonite. Traces of the cleavages as seen on a right-hand section normal to the *b*-axis.

Figure 12 illustrates the cleavages of wollastonite as seen in the plan of a right-hand termination. The most perfect cleavage, after *a*(100), is given in continuous lines; the perfect but slightly less easy cleavages after α ($\bar{1}02$) and *c*(001) are shown in broken lines; the imperfect cleavages after *v*(101) and *t*($\bar{1}01$) are indicated by short broken lines.

OPTICS.

The optical constants of wollastonite have been determined by Des Cloiseaux (1862, p. 50), Lévy and Lacroix (1888, p.

271), Spencer (in Collins, 1903, p. 259), Wright (1906, p. 104; 1915, p. 6), Larsen (in Eakle, 1917, p. 338), Osborne (1931, p. 295), McLintock (1932, p. 218), Bowen (1933, p. 91) and others. None of these observers has given quite complete data, but as far as they go they agree within narrow limits. Except for Bowen, previous observers all found the plane of the optic axes to lie normal to the axis of the cleavage zone with the acute negative bisectrix lying in the acute axial angle β. The optic axial angle is given as small; the principal indices of refraction range as follows: $X = 1.614 - 1.621$, $Y = 1.629 - 1.633$, $Z = 1.631 - 1.636$; and the dispersion of the optic axes is observed to be perceptibly greater for red than for violet light. These observations apply to some wollastonites now known to be triclinic, some known to be monoclinic, some of unknown crystallographic character, and to the artificial mineral.

To ascertain if there is any sensible difference between the optical constants of triclinic and monoclinic wollastonite a series of careful observations were made on plates and grains from measured crystals of both kinds. Cleavage plates parallel to $a(\bar{1}02)$ and $c(001)$ proved to be the most instructive; these were mounted in known crystallographic position, immersed in oil of refractive index 1.650 between hemispheres of refractive index 1.649 on a Fedorov stage. The large clear interference figures obtained with plates of sufficient thickness, under the Leitz objective No. 2 without the converging lens, facilitated precise orientation of the axes of the indicatrix and direct measurement of the optic axial angle. Plates parallel to $a(102)$ show, in the horizontal position, a nearly centred acute bisectrix figure; they can be rotated about the axis of the cleavage zone to bring each optic axis into the vertical position. Plates parallel to $c(001)$ can be rotated to bring one optic axis and both the acute and the obtuse bisectrices into the axis of the microscope.

The results of these observations are given in Table XIII and Figures 13 and 14. The optical constants of triclinic and monoclinic wollastonite are found to be essentially alike and substantially in agreement with those previously reported. The differences in the principal refractive indices, the optic axial angle, and the inclination of the acute bisectrix to the vertical crystallographic axis are within the limits of experimental error and, therefore, insignificant. There is, however, one important difference: whereas the optic axial plane was found to be strictly normal to the axis of the cleavage zone in monoclinic wollastonite, in triclinic wollastonite this plane was found to be inclined to the axis of the cleavage zone at 4°. This inclination is given by the extinction angle against the cleavage traces when the crystallographic c-axis is vertical. As a triclinic plate is turned about the horizontal b-axis in either direction, the extinction angle decreases to zero. With the acute bisectrix vertical the extinction angle was found to be 2½°; in this position Bowen[8] (1933, p. 92) observed extinction angles of 1½-2°, also on Crestmore material.

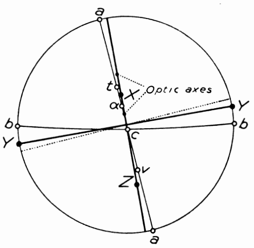

Fig. 13. Wollastonite (triclinic). Optical orientation.

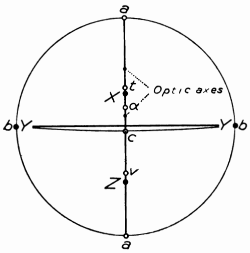

Fig. 14. Parawollastonite (monoclinic). Optical orientation.

Since the small extinction angle in plates parallel to the b-axis is the sole optical means of distinguishing the triclinic wollastonite from the monoclinic mineral, the writer turned over his preparations to Professor Larsen and Mr. Berman for critical examination with different instruments. Both observers expressed themselves satisfied that the oblique extinction of the triclinic mineral is real and appreciable.

TABLE XIII.

Wollastonite. Optical Elements.

Crestmore (triclinic)	Monte Somma (monoclinic)
X (acute bisectrix) $= 1.620$	X (acute bisectrix) $= 1.620$
$Y = 1.632$ ± 0.003	$Y = 1.631$ ± 0.003
$Z = 1.634$	$Z = 1.633$
X : c-axis $= 31½° \pm 3°$ (nearly in the acute axial angle β).	X : c-axis $= 34° \pm 3°$ (in the acute axial angle β).
Y : b-axis $= 4° \pm 1°$ (in the plane normal to the c-axis).	$Y = b$-axis.
$2V = 39° \pm 3°$; $r > v$.	$2V = 44° \pm 3°$; $r > v$.

[8] Bowen's paper was received after the writer's observations on wollastonite were completed.

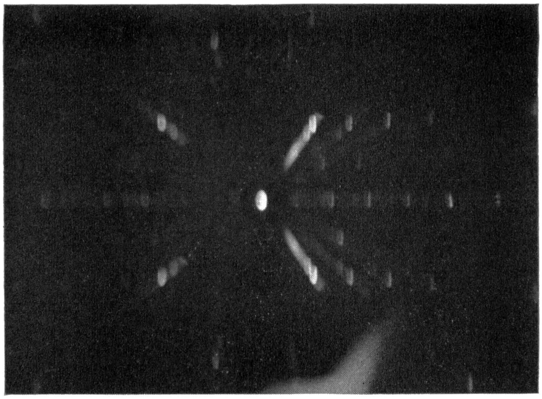

Fig. 1.

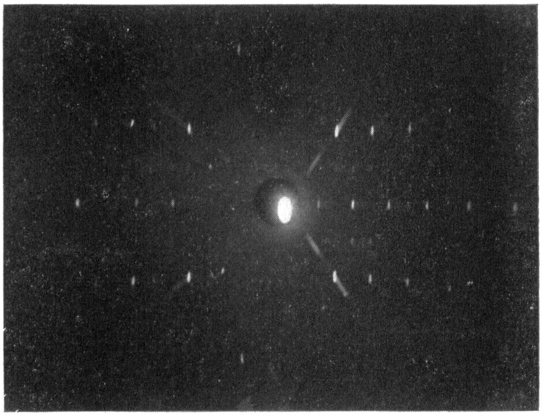

Fig. 2.

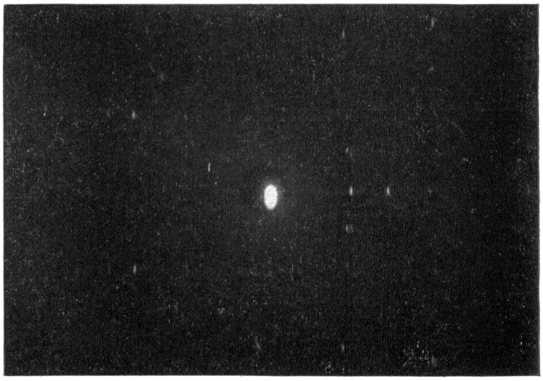

Fig. 3.

Plate I.

Plate I, Fig. 1. Wollastonite (triclinic), Crestmore, California. X-ray oscillation photograph with the beam normal to the *b*-axis. The diagram is asymmetric, with pseudo-monoclinic symmetry due to symmetry of only the even layer lines about the equator.

Plate I, Fig. 2. Parawollastonite (monoclinic), Monte Somma, Italy. X-ray oscillation photograph with the beam normal to the *b*-axis. The diagram shows true monoclinic symmetry with each spot repeated both in position and intensity about the plane of the equator.

Plate I, Fig. 3. Parawollastonite (monoclinic), Monte Somma. Similar to Fig. 2 with the crystal turned into another position about the *b*-axis. The diagram is also symmetrical about the plane of the equator.

Unequivocal orientation of the indicatrix in triclinic wollastonite is best given by the two-circle angles of the axes of the indicatrix referred to the crystallographic *c*-axis as pole and the meridian through *b*(010) as zero meridian.

	ϕ	ρ
X	—99½° ± 1°	31½° ± 3°
Y	— 9½ ± 1	90
Z	80½ ± 1	58½ ± 3

STRUCTURE SYMMETRY.

As a final and essential test of the existence of hitherto undifferentiated triclinic and monoclinic forms of wollastonite, X-ray oscillation photographs were made on measured crystals of both types. (Plate I).[9] In each case these photographs were taken with the X-ray beam normal to the *b*-axis, the spots on the equator thus representing planes in the cleavage zone [*a c*].

The photograph of the triclinic crystal from Crestmore, (Plate I, Figure 1) is exactly similar to Warren's published photograph (1931, Plate I, Figure c) of wollastonite from Chiapas, Mexico, in the same position. The diagram is that of a triclinic structure without true symmetry. As Warren pointed out in connection with the Chiapas diagram (1931, p. 401), all the spots on the even layers of the Crestmore diagram are symmetrical about the plane of the equator, but the spots on the odd layer lines are not. The Monte Somma diagrams (Figures 2, 3), on the other hand, are completely symmetrical about the plane of the equator which is, therefore, the reflection plane of symmetry of a monoclinic structure.

THREE MODIFICATIONS OF CALCIUM METASILICATE.

Artificial calcium metasilicate was first prepared by Bourgeois (1882) who recognized the crystals he obtained as monoclinic with a very small optic axial angle, unlike natural wollastonite. Allen, White and Wright (1906) named the nearly uniaxial artificial mineral pseudo-wollastonite and showed that this is the stable form of calcium metasilicate above about 1180°. In this study Wright found confirmation of Bourgeois' conclusion on the monoclinic symmetry of the

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[9] For these photographs the writer is indebted to Professor B. E. Warren, of the Massachusetts Institute of Technology.

artificial product, in opposition to Doelter (1886, p. 121), who regarded pseudo-wollastonite as hexagonal or orthorhombic, and Vogt (1892, p. 57) who considered the material as uniaxial with anomalous opening of the interference cross. In a later study Rankin and Wright (1915, p. 5) denoted pseudo-wollastonite (now spelt without a hyphen) as $\alpha CaO.SiO_2$ and natural wollastonite as $\beta CaO.SiO_2$. Recently McLintock (1932, p. 219) has described pseudo-wollastonite as a natural mineral in marls metamorphosed by the combustion of hydrocarbons. Following Dana-Ford (1932), pseudowollastonite is applied to the high temperature modification of calcium metasilicate which is easily distinguished from common natural wollastonites by its distinctive optical properties.

The morphological, optical and röntgenographic observations in this paper show that common wollastonite occurs in two closely related modifications, one belonging to the triclinic system, the other to the monoclinic. The terms "triclinic wollastonite" and "monoclinic wollastonite" used in this paper are cumbersome and mutually contradictory. It seems axiomatic that a mineral name should be associated with only one combination of fundamental physical properties, and that two minerals with distinct morphology, optics and structure should, therefore, have distinct names even though their gross chemical composition be the same. Although the ultimate structures of the two modifications of wollastonite are not yet known, it is certain that they will be found to have much in common; and, therefore, it would be undesirable to have unconnected names for the two modifications.

Wollastonite and parawollastonite suggest themselves as suitable names, wollastonite for the normal mineral and parawollastonite for the rarer paramorphic modification. The present study has shown that the wollastonite forming the massive deposit at Crestmore is the triclinic modification. Warren's work (1931) has demonstrated the triclinic character of the material from Chiapas, Mexico. From powder photographs Wyckoff, Merwin and Washington (1925) showed that the wollastonite from Diana, New York, gives the same pattern as pectolite which is now known to be triclinic; contact measurements on the great rough crystals from that locality showed that they are terminated mainly by the triclinic prism H(110), previously described as the monoclinic prism h(540) (Penfield in Dana, 1892). Against these relatively frequent and massive deposits of triclinic wollastonite the scanty occurrences of monoclinic wollastonite in the ejected limestone blocks of Vesuvius and Santorin take a subordinate place. Triclinic wollastonite is the type member of a numerous isomorphous series whereas monoclinic wollastonite has no corresponding affiliations. Finally Phillips' original goniometric work on wollastonite (1823, p. 23) led him to conclude that the mineral is indistinguishable from tabular spar whose primitive form he found to be a "doubly inclined" prism. It thus seems necessary to regard the triclinic modification as the normal one properly entitled to the name wollastonite; the name parawollastonite is, therefore, proposed for the rarer monoclinic modification.

It is natural to suppose that wollastonite and parawollastonite have different stability ranges, but the evidence bearing on this question is slender and undecisive. The great wollastonite deposits, such as those at Crestmore, Diana and Chiapas, appear to be composed mainly of wollastonite, *sensu stricto.* Since they have evidently been formed under contact metamorphic conditions with rising temperature, it would seem that wollastonite has the lower temperature of formation; in that case the natural modifications of calcium metasilicate would read: wollastonite, parawallastonite, pseudowollastonite, in order of increasing temperature of formation. This possibility is indicated by one occurrence in a Vesuvian block, in which a needle of wollastonite, evidently of later formation and presumably at lower temperature, is attached to the termination of a crystal of parawollastonite. On the other hand, the occurrence of wollastonite and parawollastonite intimately associated and in some cases apparently intergrown in the Vesuvian block suggests that there is no significant difference in the stability ranges of the two low temperature modifications.[10]

It is not surprising that wollastonite and parawollastonite have not been definitely distinguished in the past. Measurable crystals of both modifications are rare, and since they have the prismatically developed zone [*a c*] in common, terminated crystals are necessary to distinguish the triclinic and monoclinic modifications. Due simply to the fact that the known European occurrences are mainly parawollastonite while wol-

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[10] A similar case is presented by carborundum which occurs in three structurally and crystallographically distinct modifications (Peacock and Schroeder, 1934). Small crystals from electric furnace charges are found to consist of two and sometimes even three modifications in parallel growth.

lastonite is the principal material in the described American deposits, the descriptions of the morphologists refer chiefly to the monoclinic mineral whereas the triclinic mineral was that used by the röntgenographers.

The Wollastonite Group.

	Triclinic $a : b : c$	α	β	γ
Wollastonite 6 [$CaO.SiO_2$]	1.0816 : 1 : 0.9649 Grosser-Peacock	90°00′	95°16′	103°22′
Bustamite 6 [$(Ca, Mn) O.SiO_2$]	....			
Vogtite 6 [$(Ca, Fe, Mn, Mg) O.SiO_2$]	1.076 : 1 : 0.9643 Hlawatsch-Bowen	90°43′	95°10′	103°35′
Pectolite $H_2O.Na_2O.4CaO.6SiO_2$	1.1369 : 1 : 0.9963 Peacock	90°23½′	95°14′	102°42½′
Schizolite $H_2O.Na_2O.4(Ca, Mn) O.6SiO_2$	1.1061 : 1 : 0.9863 Bϕggild	90°11′	94°46′	103°07′
Rosenbuschite $6(Ca, Na) (O, F).2(Zr, Ti) O_2.4SiO_2$[11]	1.1951 : 1 : 0.9572 Brϕgger-Peacock	90°00′	101°31′	102°04½′

In the above table the known minerals with close chemical and morphological affinities to wollastonite are assembled as the wollastonite group. They form an isomorphous group with the normal triclinic wollastonite (wollastonite, *sensu stricto*), the simple metasilicate of lime, as the type member. Warren (1931, p. 400) showed that the wollastonite unit cell contains six times $CaSiO_3$. The formulas of the other members of the group have been recast on the assumption that they also have eighteen atoms of oxygen in the unit cell.

Bowen, Schairer and Posnjak (1933, p. 266) have recently prepared a series of solid solutions of $CaSiO_3$ and $FeSiO_3$ with up to 76 per cent of the latter component. The compounds give typical wollastonite powder diagrams and are, therefore, iron wollastonites. They are not known in nature and have not been prepared in measurable crystals.

There is some doubt as to whether bustamite is to be regarded as a lime rhodonite or a manganese wollastonite. Wyckoff, Merwin and Washington (1925, p. 395) obtained a characteristic wollastonite diffraction pattern from bustamite supplied by Shannon and showed that this pattern is different from that given by rhodonite. Bowen, Schairer and Posnjak

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[11] Reformulated by H. Berman from the original analyses.

(1933, p. 270) likewise obtained a typical wollastonite powder pattern from bustamite from New Jersey. In the absence of measurable crystals the evidence indicates that bustamite is a manganese wollastonite.

Bowen (1933) showed that vogtite, which is known only in slags, is isomorphous with wollastonite when the *c*-axis of Hlawatsch (1906) or of Hallimond (1919) is taken as the *b*-axis. With a typical wollastonite diffraction pattern, given by Bowen, Schairer and Posnjak (1933, p. 270), vogtite is evidently an iron-manganese wollastonite.

Pectolite was shown by Warren (1931, p. 400) to be triclinic and isomorphous with wollastonite. With water and soda replacing two of the six molecules of lime, pectolite may be regarded as hydrous soda wollastonite. A recent morphological study by the present writer (1934 B) has given precise geometrical elements.

In composition, schizolite is a manganese pectolite or a hydrous soda bustamite. The crystallographic elements are close to those of the other members of the group.

Rosenbuschite was described by Brφgger (1890) as a monoclinic mineral with a prismatically developed orthodome zone and *h*(540) as the only terminal form. It seems more than probable that this form is the triclinic prism (110), as proved to be the case in wollastonite wrongly described as monoclinic. On this basis we obtain the triclinic elements given. They differ appreciably from those of wollastonite, as might be expected from the complicated composition, and, therefore, the inclusion of rosenbuschite in the wollastonite group is to be regarded as provisional pending further morphological or röntgenographic observations.[12]

Wollastonite of the recently recognized triclinic modification is thus the type member of an important group of chemically and crystallographically related metasilicates, distinct from the pyroxenes, as was anticipated by Haüy over a century ago. The relations brought out in this paper may suggest an attempt at the difficult problem of determining the precise positions of $6CaSiO_3$ in a triclinic cell. This knowledge would undoubtedly illumine the morphological relations of wollastonite and parawollastonite and their common cleavage and twinning characteristics.

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[12] A preliminary determination of the unit cell of rosenbuschite, by T. F. W. Barth and C. J. Ksanda, gave triclinic elements with an axial angle α nearly 90°, roughly comparable to those computed above.

SUMMARY.

A study of wollastonite crystals from Crestmore, California, and Monte Somma, Mount Vesuvius, Italy, together with an examination of the published descriptions of wollastonite, show that this mineral, hitherto variously described as triclinic or monoclinic, comprises two modifications, one triclinic, the other monoclinic. It is proposed to restrict the name wollastonite to the commoner triclinic mineral typically developed in large bodies of contact-metamorphosed limestone, and to apply the name parawollastonite to the rarer monoclinic modification that is found chiefly in limestone blocks ejected from volcanoes.

Wollastonite and parawollastonite have many characteristics in common: both are elongated with the *b*-axis and have the zone [*a c*] and the crystallographic elements *b*, *c*, and p_0, r_0, μ in common; both form twins on *a*(100) and have the same cleavages, namely *a*(100) perfect and easy, $\alpha(\bar{1}02)$ and *c*(001) perfect and less easy, *v*(101) and $t(\bar{1}01)$ poor; the two modifications have the same general optical scheme and give similar oscillation X-ray photographs. Wollastonite is distinguished from parawollastonite by a completely different asymmetric series of terminal forms, a perceptible inclination of the optic axial plane to the plane normal to the *b*-axis, and an asymmetric system of X-ray interference spots.

Wollastonite and parawollastonite are both low temperature forms of calcium metasilicate comprised in the $\beta CaO.SiO_2$ of Rankin and Wright. There are indications that wollastonite has the lower stability range, but the evidence is not conclusive.

Wollastonite, vogtite, pectolite and schizolite form an isomorphous group with which are classed the artificial iron wollastonites of Bowen, bustamite which is not known in measurable crystals, and the mineral rosenbuschite.

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