ART. V.—*Lawsonite from the Central Coast Ranges of California*; by AUSTIN F. ROGERS.

OF the new rock-forming minerals described within the last decade or two, lawsonite, a basic calcium aluminum silicate, is one of the most interesting if not important. Though usually an accessory constituent, in some cases it proves to be an essential constituent of certain rocks. The type locality of lawsonite is Tiburon Peninsula in Marin County, California, where it was found by Ransome¹ and by Palache² almost simultaneously. Since its discovery in 1894 it has proved to be a widely distributed mineral, for it has been observed by Franchi³ in the glaucophane rocks in the Piedmont Alps, by Viola⁴ in the diabases and gabbros of southern Italy, by Lacroix⁵ in the glaucophane schists of Corsica and the gabbros of Corsica and New Caledonia, by Manasse⁶ in the island of Gorgona, and by Termier⁷ in the glaucophane schists of the department of Hautes-Alpes. In the coast ranges of California lawsonite is a fairly common constituent of the metamorphic rocks of the Franciscan series, as has been pointed out by J. P. Smith⁸ and by Eakle⁹.

Lawsonite occurs in orthorhombic crystals of simple habit, which are usually tabular or prismatic. The common forms are $m\{110\}$, $c\{001\}$, $b\{010\}$, and $d\{011\}$, with $mm\{110:1\bar{1}0\} = 67^\circ 16'$, and $dd(011:0\bar{1}1) = 72^\circ 53\frac{1}{2}'$. Hillebrand and Schaller¹⁰ give in addition the forms $e\{041\}$, $r\{221\}$, and $s\{331\}$. The specific gravity is 3.12 and the hardness 7–8. The color is grayish-white to bluish-gray.

The optical orientation of lawsonite is $a=a$, $\beta=b$, $\gamma=c$. The indices of refraction as given by Ransome¹ are $n_\gamma = 1.684$, $n_\beta = 1.669$, $n_a = 1.665$; $n_\gamma - n_a = .019$. Basal sections are usually rhombic in outline, with first order interference colors, while the other sections are rectangular with second order interference colors. The basal sections often show polysynthetic twinning with $m\{110\}$ as twin-plane.

Chemically, lawsonite is interesting because it corresponds to anorthite with two molecules of water added. The empirical formula is $H_4CaAl_2Si_2O_{10}$, as proved by the following analyses which are the only complete analyses available. The last analysis of this list (No. VI) is a new one of lawsonite from Alameda County, California, which is described beyond.

There are two characteristic kinds of occurrence of lawsonite. (1) As a secondary mineral in slightly altered or saussuritized diorites and gabbros. California, Corsica, Piedmont Alps, Gorgona, and New Caledonia. (2) As an accessory or

ANALYSES OF LAWSONITE							
		I	II	III	IV	V	VI
Theory		Tiburón,	Tiburón	Tiburón,	Rocca	Mairatale,	Arroyo
$H_2CaAl_2Si_2O_{10}$		Ransome ¹	Palache ¹	Hillebrand & Schaller ¹⁰	Niera, Italy Zam- bonini ¹¹	Italy Zam- bonini ¹¹	Mocho, Calif. Small
38.34	SiO ₂	38.10	37.32	38.45	38.37	38.21	38.10
32.44	Al ₂ O ₃	28.88	35.14	31.35	32.27	31.98	32.21
	Fe ₂ O ₃	0.85		0.86	0.23	tr	nil
	FeO	----	----	0.10	----	----	nil
	MnO	----	----	tr	----	----	nil
	MgO	0.23	----	0.17	0.18	0.25	nil
17.80	CaO	18.26	17.83	17.52	18.14	18.23	17.74
	Na ₂ O	0.65	----	0.06	0.36	n. d.	----
	K ₂ O	----	----	0.23	tr	----	----
	TiO ₂	----	----	0.38	----	----	nil
	CO ₂	----	----	----	----	----	1.12
11.42	H ₂ O	11.42	11.21	11.21	11.02	11.24	10.85
100.00		98.39	101.50	100.33	100.57	99.91	100.02

essential constituent of schists and gneisses, which usually also contain glaucophane. California, Corsica, Piedmont Alps, and Hantes-Alpes.

The opinion of J. P. Smith⁶ that lawsonite represents the anorthite portion of plagioclase set free in the chemical readjustment incident to metamorphism is well founded. The albite portion of the plagioclase contributes to the formation of glaucophane or at times crystallizes out as albite.

A dimorphous (isometric) form of $H_2CaAl_2Si_2O_{10}$ has been described by Cornu* under the name hibschite. The hibschite occurs in calcareous inclusions in phonolite at Marienberg, Bohemia, and has since been found by Lacroix† in calcareous inclusions of basalt at Ardèche in the Central Plateau, France.

With these introductory remarks, lawsonite is now described from a number of new localities in the Central Coast Ranges of California; variation in the habit is especially emphasized.

Arroyo Mocho, Alameda County.

In a prominent outcrop of glaucophane schist alongside the road near the head of the Arroyo Mocho and about eighteen miles southeast of Livermore, Alameda County, there were found seams of lawsonite, in part as coarse fibrous masses and in part as distinct crystals in cavities. The lawsonite crystals

* Min. petr. Mitt., vol. xxv, p. 249, 1906.

† Mineralogie de la France, vol. iv, p. 705, 1910.

are about 1^{cm} in length, 4^{mm} in width, and 2^{mm} thick, and in habit are prismatic in the direction of the a -axis. The forms are $d\{011\}$, $m\{110\}$, and $c\{001\}$, as represented in figure 1. This habit is so different from that of the Tiburon crystals that it was not at first suspected to be lawsonite. There is distinct cleavage parallel to m and to c . The optical orientation is $a=a$, $b=\beta$, $c=\gamma$.

FIG. 1.

FIG. 2.

FIG. 3.

FIG. 1. Lawsonite from Arroyo Mocho, Alameda County.

FIG. 2. Lawsonite from Calaveras Valley, Santa Clara County.

FIG. 3. Lawsonite from Calaveras Valley, Santa Clara County.

An analysis of this lawsonite was made by Mr. H. L. Small under the writer's direction. The results, which are the average of two, are given in column I. The lawsonite is pure except for a little calcite, which is probably an alteration product. Subtracting the carbon dioxide and an equivalent amount of lime and recalculating to 100 per cent, we have the figures of column II, while the theoretical percentages for $\text{H}_4\text{CaAl}_2\text{Si}_2\text{O}_{10}$ are given in column III.

Analysis of Lawsonite from Arroyo Mocho.

	I	II	III
SiO_2	38.10	38.70	38.34
Al_2O_3	32.21	32.60	32.44
CaO	17.74	17.70	17.80
MnO	nil	----	----
MgO	nil	----	----
TiO_2	nil	----	----
CO_2	1.12*	----	----
H_2O	10.85*	11.00	11.42
Total	100.02	100.00	100.00

* The water was determined by the Penfield tube method, while combined water and carbon dioxide were determined by loss on ignition.

Calaveras Valley, Santa Clara County.

Lawsonite crystals were found in seams of glaucophane-schist outcrop on the Sunol road in the northern end of Calaveras Valley. The crystals have the habit of figure 2 with the forms $d\{011\}$, $m\{110\}$, $c\{001\}$, and $b\{010\}$. The crystals are grayish-white, measure from 3^{mm} to 1½^{cm} in the direction of the b -axis, and greatly resemble some of the Tiburon crystals. The glaucophane-schist itself contains lawsonite, which appears to be more abundant near the seams.

Loose boulders of glaucophane-schists from the Arroyo Hondo at the northern end of Calaveras Valley contain acicular crystals in cavities and seams. The crystals, which measure only 2^{mm} in length, are elongated in the direction of the a -axis.

The forms present are $c\{001\}$, $m\{110\}$, $b\{010\}$, and $d\{011\}$, as represented in fig. 3. The optical orientation for most of the crystals is $a = \alpha$, $b = \beta$, $c = \gamma$, but some of the crystals extinguish on the (001) face in two approximate halves as indicated by fig. 4. In one part the extinction is parallel and in the other part it is about 5° to the long edge of the crystal. This possibly indicates that lawsonite is monoclinic like carpholite ($H_4MnAl_2Si_2O_{10}$), which is chemically analogous to lawsonite. According to Lévy and Lacroix* the extinction angle of carpholite is 3° to 5°.

FIG. 4.

FIG. 4. Lawsonite from Calaveras valley, Santa Clara Co.

Mt. Hamilton Region, Santa Clara County.

Minute lawsonite crystals from a narrow seam in a garnetiferous glaucophane-schist (from the Mt. Hamilton region in Santa Clara County (but exact locality unknown) are represented by fig. 5. The habit is tabular with the forms $c\{001\}$, $d\{011\}$, and $m\{110\}$. Optically they resemble the acicular crystals from Calaveras Valley.

Northeastern Santa Clara County.

Specimens of glaucophane-schist from the 3250 peak of the Mt. Hamilton topographic sheet of the United States Geological Survey, which is about ten miles northeast of Mt. Hamilton, contain acicular crystals of lawsonite in seams and cavities. The crystals are 3 or 4^{mm} in length and are imperfect crystals with indistinct faces arranged in parallel position or in subradiating groups. There is a fairly good cleavage parallel to the length of the crystals. Fragments are prismatic with parallel

* Les Minéraux des Roches, p. 164.

extinction and the elongation is parallel to the fast ray. From these tests it is evident that the crystals are prismatic in the direction of the a -axis. A rough water determination gave 12.97 per cent.

Region east of Mt. Hamilton.

Specimens of vein material in a metamorphic rock collected in the region east of Mt. Hamilton show small 3^{mm} acicular crystals of lawsonite in a matrix of quartz. In thin sections the lawsonite appears as in fig. 8. Cross-sections are irregular or rhombic with the fast ray parallel to the long diagonal

FIG. 5. Lawsonite from Mt. Hamilton region.

FIG. 6. Lawsonite from Alameda County.

FIG. 7. Lawsonite from Colorado Creek, Santa Clara County.

while longitudinal sections are elongate, rectangular with more or less frayed ends and are in part parallel to the slow ray, in part parallel to the fast ray. Hence the crystals are prismatic in the direction of the a -axis with habit something like fig. 1. The optical orientation is $a = a$, $b = \beta$, $c = \gamma$. The double refraction ($n_\gamma - n_a$), determining the thickness of the slide by taking the highest interference color of the quartz, is .022, which is a little higher than the value (.019) obtained by Ransome.¹

Southeastern Alameda County.

Boulders of a massive lawsonite-chlorite rock were found in the extreme southeastern corner of the Tesla topographic sheet of the United States Geological Survey. The lawsonite occurs in tabular crystals of 5^{mm} diameter and $\frac{1}{2}$ ^{mm} thickness. The forms are $c\{001\}$, $m\{110\}$, and $b\{010\}$.

The habit is pseudo-hexagonal due to equal development of m and b , though the angle ($110 : 1\bar{1}0$) is 67°. The optical orientation is $a = a$, $b = \beta$, $c = \gamma$. The rock contains lawsonite and chlorite with subordinate titanite in minute granular crystals.

Lawsonite from Colorado Creek, Santa Clara County.

This locality for lawsonite is on Colorado Creek just south of the divide between the Arroyo Mocho and Colorado Creek in the northeastern part of the Mt. Hamilton topographic

sheet. At this place Mr. R. V. Anderson found a large boulder of a chlorite-lawsonite rock. The lawsonite occurs in well-defined crystals of rhombic tabular habit (fig. 7) with the forms $c\{001\}$, $m\{110\}$, and occasionally $b\{010\}$. The crystals appear almost black on account of the inclusions of dark green chlorite, but on weathered specimens the lawsonite is opaque white and stands out in bold relief. There is distinct cleavage parallel to $b\{010\}$ and to $m\{110\}$. Some of the basal sections show fine polysynthetic twin-lamellæ with $\{110\}$ as twin-plane.

In addition to lawsonite and chlorite this rock contains muscovite and titanite and also a little albite in veins. An analysis of the rock was made by Mr. H. F. Humphrey, formerly assistant in mineralogy at Stanford University, with the following results:

		Titanite	Lawsonite	Muscovite	Chlorite
SiO ₂	38.12	1.02	14.41	10.99	11.70
Al ₂ O ₃	25.81	----	12.54	9.43	4.04
Fe ₂ O ₃	0.13	----	----	----	----
FeO	9.86	----	----	----	9.86
MgO	6.50	----	----	----	6.50
CaO	7.62	0.93	6.69	----	----
Na ₂ O	0.50	----	----	0.50	----
K ₂ O	2.11	----	----	2.11	----
H ₂ O—	0.11	----	----	----	----
H ₂ O+	8.16	----	4.29	1.09	2.78
TiO ₂	1.35	1.35	----	----	----
	<hr/>	<hr/>	<hr/>	<hr/>	<hr/>
	100.27	3.36	37.93	24.02	34.88

The percentages of the mineral may be calculated from the chemical analysis. All of the titanium oxide and an equivalent amount of lime go to make the titanite. The remainder of the lime goes to the lawsonite. All the potash and soda go to the muscovite, which may be assumed to be $H_2(K,Na)Al_2(SiO_4)_3$. All the magnesia and ferrous oxide, and the remainder of the silica, alumina, and water belong to the chlorite.

Recalculating to 100 per cent, we have the following percentage composition of the chlorite:

SiO ₂	33.5
Al ₂ O ₃	11.6
FeO	28.3
MgO	18.6
H ₂ O	8.0
	<hr/>
	100.0

This is close to an analysis of diabantite from Farmington, Conn., analyzed by Hawes.* The chlorite in this rock, it

* Dana, System of Mineralogy, 6th edition, p. 659.

should be emphasized, is not an ordinary alteration product but a recrystallized product of metamorphism.

This lawsonite-chlorite-muscovite rock mass probably represents an original gabbro or diabase. The fact that the chlorite is a diabantite chemically similar to that found in diabase points to the igneous origin.

A similar rock consisting of lawsonite, chlorite, muscovite, and titanite was collected by Mr. R. B. Moran at the Fillmore ranch in San Luis Obispo County. The lawsonite occurs in thin plates 1^{mm} thick and 6 to 8^{mm} in diameter. In a thin

FIG. 8.

FIG. 9.

FIG. 8. Lawsonite (*l*) in quartz (*q*), Mt. Hamilton region.

FIG. 9. Lawsonite in slightly altered diorite, Smith Creek, Santa Clara County (*l*, lawsonite, *h*, hornblende, *p*, plagioclase (andesine), *g*, glaucophane).

rock slide the lawsonite appears principally as long rectangular sections with parallel extinction. One elongated section has the peculiar optical properties illustrated by fig. 4. Polysynthetic twin-lamellæ are present in some crystals.

Eakle⁹ also mentions a boulder of lawsonite-chlorite rock with muscovite and titanite from North Berkeley.

Smith Creek, Santa Clara County.

In thin sections of a hornblende diorite collected by Mr. Stephen Taber on Smith Creek, near the Smith Creek Hotel, small crystals of lawsonite were identified. This rock is made up of dark hornblende in a matrix of greenish-gray feldspar. The axial colors of the hornblende are: α = pale greenish-yellow; β = deep green; γ = medium green. Absorption $\beta > \gamma > \alpha$. The hornblende is bordered on the ends by a thin fringe of glaucophane in parallel position (fig. 9). The plagioclase

clase is cloudy but shows albite twinning. Measurements of the extinction angle indicate that it is andesine, about Ab_2An_1 . Irregularly distributed through the feldspar are small, elongated lawsonite crystals with parallel extinction, bright interference-colors, and elongation parallel to the fast ray. From a study of the cross-sections it is evident that the lawsonite crystals have a habit similar to fig. 3. This rock is only slightly altered and we have here the beginning of saussuritization of the feldspars. This is an excellent example of the chemical readjustment as explained by J. P. Smith.⁸ The soda end of the plagioclase forms glaucophane while the lime end forms lawsonite.

Slightly altered igneous rocks of this type seem to be rather common in the Mt. Hamilton region. J. P. Smith⁸ mentions a quartz-diorite from Oak Ridge, Santa Clara County, in which the original minerals are oligoclase, katophorite-like hornblende, and quartz. The secondary minerals are lawsonite and crossite.

Lawsonite-glaucophane Schists.

In addition to the localities mentioned in this paper and by J. P. Smith⁸ in his valuable paper on the glaucophane-bearing rocks, I have studied lawsonite-bearing glaucophane-schists from the following localities:

Hubbard Ranch, Isabel Creek, Santa Clara Co. Isabel Valley, Santa Clara Co. L'Ecuyer's Ranch, Arroyo Mochó, Alameda Co. Southern end of Tesla topographic sheet, Alameda Co. Cedar Mountain, Alameda Co. Yager, Humboldt Co. (collected by Mr. W. G. Cooper).

Thelen¹² also mentions lawsonite as a constituent of the glaucophane schists of North Berkeley, California.

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