

# THE AMERICAN MINERALOGIST

JOURNAL OF THE MINERALOGICAL SOCIETY OF AMERICA

Vol. 17

SEPTEMBER, 1932

No. 9

## BAVENITE, A BERYLLIUM MINERAL, PSEUDOMORPHOUS AFTER BERYL, FROM CALIFORNIA\*

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### ABSTRACT

Bavenite has been identified from a gem tourmaline mine at Mesa Grande, California. This is the second recorded occurrence of this mineral, previously described from Baveno, Italy. Bavenite is a beryllium mineral, with about 3 per cent of BeO. The Italian bavenite also contains beryllium, not previously recognized. Three new crystal forms are determined; the optical properties are given, correcting an error in the optical orientation as published; and the chemical analysis leads to the formula  $9\text{SiO}_2 \cdot \text{Al}_2\text{O}_3 \cdot \text{BeO} \cdot 4\text{CaO} \cdot \text{H}_2\text{O}$ , with some uncertainty as to the exact ratio of the  $\text{SiO}_2$  and  $\text{H}_2\text{O}$ . The California occurrence is a new pseudomorph after beryl.

### INTRODUCTION

Bavenite was described by Artini<sup>1</sup> in 1901, as groups of prismatic crystals in pegmatitic druses in the granite of Baveno, Italy. No further records of additional occurrences were found in the literature. Artini assigned to the mineral the formula  $3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot \text{H}_2\text{O}$ , having no reason for suspecting the presence of beryllium. Some years ago Mr. E. Schernikow of San Francisco, kindly presented to one of the writers (W.T.S.) a specimen of a fine-grained white pseudomorph after a flattened crystal of beryl, from the Himalaya mine, Mesa Grande, San Diego County, California, the mine famous for its many wonderful tourmalines and other associated minerals. Only recently did an opportunity occur for analyzing this pseudomorphous mineral, for it was realized that being an alteration product of beryl it might contain beryllium and one of the writers (J.G.F.) had just finished a comparison of the

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<sup>1</sup> Artini, Ettore, Di una nuova specie minerale trovata nel granito di Baveno: *Atti d. Reale Accad. dei Lincei, Rendic., classe sci. fis., mat. e nat.*, vol. 10, pp. 139-145, 1901. Abstr. in *Zeitschr. f. Kryst. u. Min.*, vol. 37, pp. 389-391, 1903. There are two errors in the abstract: The cleavage is given as (100), it should read (010); and ptilolith should read pilonith.

various analytical methods for separating small quantities of beryllium from aluminum. The analysis of the mineral from Mesa Grande showed it to contain 2.67 per cent BeO, but otherwise it is identical in composition with the bavenite from Italy.

Spectrographic tests made by George Steiger, on two specimens of bavenite from Baveno, Italy, indicate that the Italian bavenite contains fully as much beryllium as the mineral from California.

The occurrence at Mesa Grande establishes another pseudomorphous change after beryl. Dana lists kaolin, mica, limonite, and quartz as pseudomorphous after beryl. Other alterations are roosterite and pseudosmaragd. The compact fine-grained white earthy

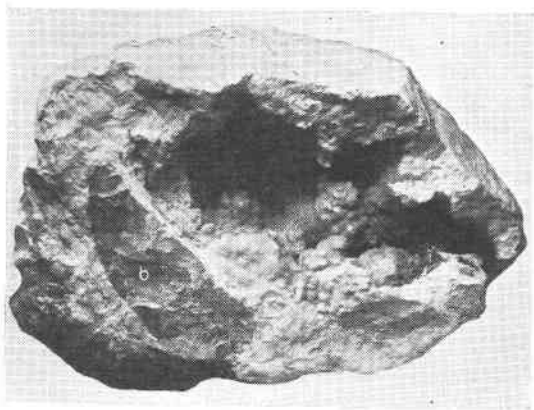


FIG. 1. Specimen of bavenite from Mesa Grande, California, pseudomorphous after beryl. Residual beryl marked *b*. Natural size.

bavenite, pseudomorphous after beryl, from Mesa Grande, California, resembles kaolin in general appearance and it is possible that such pseudomorphous bavenite, from other localities, has erroneously been called kaolin.

#### OCCURRENCE

The specimen, shown in natural size in Fig. 1, measures 3 inches across horizontally and is slightly over  $1\frac{1}{2}$  inches high. The original crystal of beryl was pink, as evidenced by the residual material (*b*, Fig. 1) embedded in the bavenite, and was a flattened crystal with large faces of  $c(0001)$  and  $s(11\bar{2}1)$ , probably similar in shape to the crystals of beryl shown by Ford<sup>2</sup> in his Figures 1, 4, 5. Both

<sup>2</sup> Ford, W. E., Some interesting beryl crystals and their association: *Amer. Jour. Science*, 4th ser., vol. 22, pp. 217-223, 1906.

faces of the base (0001) are present on the pseudomorphous specimen from California; the only other recognizable face, is the one shown in the upper right corner of Fig. 1, evidently a face of  $s(11\bar{2}1)$ . Measured  $c \wedge s = 43^\circ - 44^\circ$  (Calc.  $44^\circ 56'$ ).

The original crystal of beryl has been almost completely changed to a fine-grained, compact, white chalky-looking material, soft, easily rubbing off and soiling the fingers. Considerable albite and smaller quantities of pink tourmaline, lepidolite, quartz, and black specks of manganese oxide are partially embedded in the outside of the specimen. Although showing no definite structure to the unaided eye, an examination with a hand lens on a freshly broken surface shows that much of the bavenite has a fibrous character.

The specimen was broken in halves, with the hope of finding some unaltered beryl remaining in the center. This hope was fulfilled as such a residual mass of pink beryl, slightly over an inch long, was found embedded in the white bavenite. (See (b) Fig. 1.) This beryl is typical of the alkali-containing beryls, with refractive indices slightly higher than ordinary beryl. This residual pink beryl has  $\omega = 1.585$ ,  $\epsilon = 1.578$ . Ford<sup>3</sup> found  $\omega = 1.58157$  for a pink beryl from Mesa Grande with 1.48 per cent alkali oxides ( $K_2O$ ,  $Na_2O$ ,  $Li_2O$ , with no  $Cs_2O$ ). When the pseudomorphous crystal was broken in two, a cavity was found in its center, whose walls are composed of aggregates of fibrous spherulites of bavenite. The cavity is somewhat flattened parallel to the base of the original beryl crystal. The compact bavenite surrounding the cavity is fibrous, mostly radiating but partly parallel. The surfaces of the spherulites of bavenite in the cavity are covered with minute bristling lath-shaped prismatic crystals, which, with the hand lens, can be seen to be terminated by long narrow dome faces, as shown in Figures 2 and 3.

A small cavity on the surface of the specimen, probably formed by the removal of a crystal of tourmaline, was lined with minute terminated crystals, on one side in parallel grouping and on the other sides in radiating fibrous masses.

Part of the mass of residual beryl showed the penetrating character of the bavenite as fibrous masses projecting irregularly into the beryl and as replacing the beryl along the many fractures.

<sup>3</sup> Ford, W. E., The effect of the presence of alkalis in beryl upon its optical properties: *Amer. Jour. Science*, 4th ser., vol. 30, p. 129, 1910.

## CRYSTALLOGRAPHY

Before measuring the minute crystals of bavenite from California, four crystals from the type locality at Baveno, Italy, were measured. These agreed in habit, form development, and angular values with those given by Artini. Each of the flattened crystals was terminated by two dome faces on both the front and the rear sides, as illustrated by Artini in his crystal drawing of bavenite (his Fig. 1). However, only one of these forms corresponds to the dome (101) given by Artini, the other face being a new dome (201), present on each of the four crystals measured. Artini's form (103) was not observed; he describes it as rather rare being found only on three of his best crystals with one face on each crystal. As the dome (201) was present on each of the four measured crystals from Italy as well as on those from California, it would appear to be a characteristic form for bavenite and it seems strange that it was not present on the crystals measured by Artini. In addition to the forms given by Artini, with the exception of (103), the clinopinacoid (010) and the clinodome (012) as well as the new dome (201), were also observed on the crystals from Baveno, Italy.

Artini has shown that the crystals are pseudo-orthorhombic, being monoclinic, twinned on the front pinacoid  $a(100)$ . As a result, the crystals appear orthorhombic in symmetry, on the one terminated end.

Two different orientations are suggested by Artini. Plotting the measurements (by W.T.S.) direct on a gnomonic projection, it is seen that the best orientation is the one in which his form (103) becomes the base (001). The only terminal form, in addition to those in the front dome zone  $(001) \wedge (100)$ , then becomes the clinodome (012), retaining the indices of the two prisms as given by Artini.

The crystal elements of bavenite are then:  $a:b:c=1.2006:1:0.5230$ ,  $\beta=78^{\circ}08'$  (Artini). The table below gives the calculated angles and the average of the measured angles. All the measurements were poor and not suitable for calculation of new crystal elements as they showed variations of several degrees. However, the averages of the measured angles are, except for the prism (210), very close to those given by Artini. Thus, the  $\phi$  angle for  $m(110)$  is  $40^{\circ}39'$  (Artini,  $40^{\circ}24'$ ), the  $\rho$  angle for  $u(101)$  is  $33^{\circ}12'$  (Artini,  $33^{\circ}14'$ ). From the  $\phi$  and  $\rho$  measurements of  $e(012)$ , the value of  $\beta$  is obtained direct and found to be  $78^{\circ}12'$  (Artini  $78^{\circ}08'$ ). Only



position for this form. The measurements for the new forms are as follows:

$$\phi \text{ for } b(010) = 1^{\circ}27', 2^{\circ}18', 3^{\circ}54'$$

$$\rho \text{ for } d(201) = 47^{\circ}30', 47^{\circ}08', 48^{\circ}15', 49^{\circ}55', 48^{\circ}45'.$$

The two best measurements for  $e(012)$  are given in the first two lines below, followed by three additional measurements (in parenthesis) of extremely minute faces of  $e(012)$  which gave no reflection but were measured by their position of maximum brightness.

Measurements of  $e(012)$

$\phi$	$\rho$
$37^{\circ}39'$	$19^{\circ}30'$
$36\ 59$	$18\ 32$
$(42^{\circ})$	$(22^{\circ})$
$(32^{\circ})$	$(20^{\circ})$
$(33^{\circ})$	$(19^{\circ})$

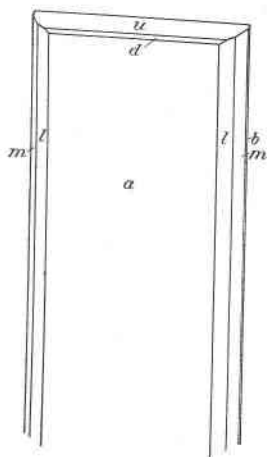


FIG. 2

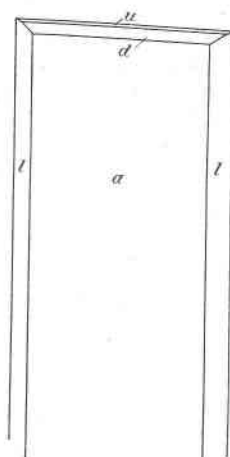


FIG. 3

FIG. 2. Bavenite crystal from Italy. Forms:  $a(100)$ ,  $b(010)$ ,  $m(110)$ ,  $l(210)$ ,  $u(101)$ ,  $d(201)$ . The crystals are monoclinic, twinned on  $a(100)$  and consequently simulate orthorhombic symmetry.

FIG. 3. Bavenite crystal from California. Forms:  $a(100)$ ,  $l(210)$ ,  $u(101)$ ,  $d(201)$ .

The habit of the crystals from the two localities is very similar. Both are platy prismatic, the front pinacoid  $a(100)$  being the dominant form. The entire prism zone is strongly striated. The termination is determined by front domes somewhat striated parallel to their intersection; Artini gives these as  $(101)$  and  $(103)$  which in

the orientation here chosen become (101) and (001). In the four crystals from Italy here described, no face of (001) (Artini's (103)) was observed, but each crystal had faces of  $d(201)$ , a form not found by Artini. Two of the crystals also had minute faces of  $e(012)$ . On the specimen studied (from Italy) the crystals have the characteristic combination  $a, b, m, l, u, d$ , Fig. 2. The crystals from California are very similar showing  $a, l, u, d$ , Fig. 3. In general the faces of  $u(101)$  are larger than those of  $d(201)$  on the crystals from Italy whereas on those from California, the faces of  $d(201)$  are the larger,  $u(101)$  being a mere line face. Three faces of  $e(012)$  were measured at one end of one of the crystals from Italy, showing that the crystal is twinned on  $a(100)$ .

OPTICAL PROPERTIES

Observations under the microscope, with determinations of the quantitative values, have shown the complete identity of the bavenite from the two localities. The crystals from California are so minute, about a tenth of a millimeter wide, that their monoclinic symmetry would probably not have been noticed. But a special study of the crystals has shown that their apparent orthorhombic symmetry is due to twinning on the front pinacoid  $a(100)$  and

OPTICAL PROPERTIES OF BAVENITE

	Italy			California			Average
	Artini	Larsen <sup>a</sup>	Schaller	Schaller		Ross <sup>b</sup>	
				Fibers	Crystals	Fibers	
$\alpha$ .....	.....	1.578	1.580	1.580	1.579	1.580	1.579
$\beta$ .....	1.580	1.579	1.582	—	1.581	—	1.581
$\gamma$ .....	.....	1.583	1.590	1.588	1.589	1.587	1.587
2V.....	47°	Small	.....	.....	.....	58°	.....
2E.....	78½°	.....	.....	.....	.....	103°	.....
Sign.....	+	+	+	.....	+	+	+
Elong.....	.....	.....	—	—	—	—	—
Ext.....	2°	Very small	.....	.....	2°	.....	2°
Orientation..	Z=b	Z=b	Z=b	.....	Z=b	.....	Z=b

<sup>a</sup> Larsen, E. S., The microscopic determination of the nonopaque minerals: U. S. Geol. Survey., Bull. 679, p. 44, 1921.

<sup>b</sup> Personal communication.

cleavage fragments parallel to  $b(010)$  show this twinning with the two parts extinguishing about  $4^\circ$  apart with consequent extinction against the vertical axis of  $2^\circ$ .

The determinations of the optical properties of bavenite are summarized in the table above. The mineral is colorless, nonpleochroic, and shows no differential absorption.

Artini has the axial plane in the wrong position in his Fig. 2. He gives it as parallel to the elongation whereas it is across the elongation, being approximately parallel to the basal pinacoid. The obtuse bisectrix ( $X$ ) emerges nearly normal to (100) and the acute bisectrix ( $Z$ ) emerges normal to (010). This relationship, namely that the axial plane lies nearly normal to the elongation and not parallel to it, was determined on bavenite crystals from Italy as well as on those from California. The correct orientation is given by Larsen. With the crystallographical axes used in this paper, namely  $a:b:c = 1.2006:0:0.5230$ ,  $\beta = 78^\circ 08'$ , the optical orientation of bavenite is:

$$\begin{aligned} X \wedge a \text{ axis} &= 10^\circ \text{ (above)} \\ Y \wedge c \text{ axis} &= 2^\circ \text{ (in front)} \\ Z &= b \text{ axis} \end{aligned}$$

#### CHEMICAL COMPOSITION

Being pseudomorphous after beryl, the bavenite from California, is naturally thought of as containing beryllium and spectrographic tests, kindly made by George Steiger, showed definitely that beryllium is present, in quantity greater than a trace. Chemical separation and determination (by J.G.F.) verified the presence of beryllium to an extent of nearly 3 per cent.

Additional tests made on two samples of bavenite from Baveno, Italy, (U. S. National Museum Cat. Nos. 85180, the same specimen on which Larsen made his optical determinations, and R4158 (Roebing collection)) showed that they too contained beryllium, in quantity similar to that from California. The results of Mr. Steiger's spectrographic tests on bavenite are given in Fig. 4.

In this figure, the upper black band on each chart, labelled beryllium, shows the four characteristic lines of beryllium at 2494, 2650, 3130, and 3321 Ångstrom units. The upper black band was made with beryllium metal. The correspondence of the four lines of beryllium in the spectrum of each of the three specimens examined, with the beryllium standard lines, at the wave lengths given, is clearly shown. The upper spectrograph of bavenite from



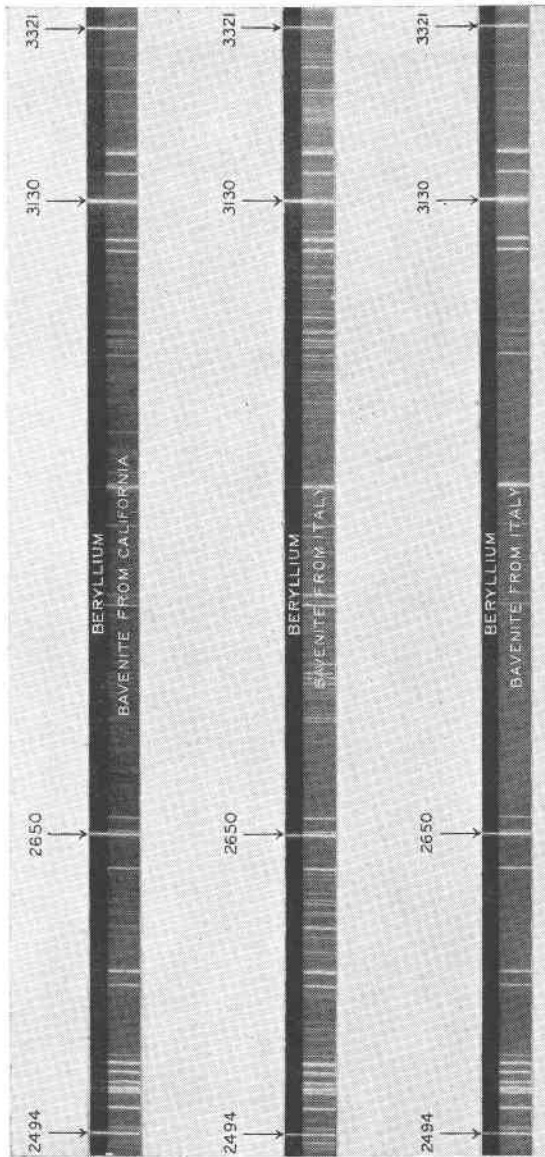


FIG. 4. Charts showing spectrographic identification of beryllium in bavenite from California and from Italy. (Spectrographs taken by George Steiger).

Italy is from specimen U. S. Nat. Mus. No. R4158 and the lower spectrograph is from specimen U. S. Nat. Mus. No. 85180.

A sample of the bavenite from California was prepared for analysis, being carefully purified by hand picking and particularly freed from any admixed beryl. Its analysis is given below with the ratios calculated therefrom.

ANALYSIS AND RATIOS OF BAVENITE FROM MESA GRANDE, CALIFORNIA  
[J. G. Fairchild, analyst]

	Analysis	Ratios	
SiO <sub>2</sub> .....	58.40	.9717	8.99 or 9
Al <sub>2</sub> O <sub>3</sub> .....	12.16	.1192	1.10 or 1
BeO .....	2.67	.1068	0.99 or 1
CaO .....	23.73	.4230	3.91 or 4
H <sub>2</sub> O .....	2.90	.1611	1.49 or 1½
Fe <sub>2</sub> O <sub>3</sub> .....	0.10		
	99.96		

The determinations were made in duplicate, with close checks for the CaO and SiO<sub>2</sub>. The beryllia was separated from the alumina by the method of Noyes and Bray in which BeO is separated from Al<sub>2</sub>O<sub>3</sub> in HCl-ether solution, followed by the treatment of their acetates with chloroform in which the BeO compound is soluble. By this procedure known quantities of BeO were recovered from admixed material high in Al<sub>2</sub>O<sub>3</sub>. When such a solution containing beryllium is freed from chloroform, treated with turmeric, and then made ammoniacal, a characteristic claret-colored lake is formed.

The loss of water by ignition, was as follows:

TOTAL H<sub>2</sub>O LOST AT GIVEN TEMPERATURE, C°.

	110°	150°	300°	450°	550°-600°	Ignition
Percent loss	0.00	0.02	0.04	0.08	0.26	2.90

The ratios indicate the formula 9SiO<sub>2</sub> · Al<sub>2</sub>O<sub>3</sub> · BeO · 4CaO · 1½H<sub>2</sub>O. As discussed below, it is believed that part of the water is adsorbed and not inherent to the mineral so that the formula for the mineral is written with one H<sub>2</sub>O.

A discussion of the formula calculated from Artini's analysis of the bavenite from Italy suggests that the ratio of silica to alumina is only 8:1 and not 9:1. In the analysis of the mineral from California, the ratio of  $\text{SiO}_2$  to the other bases, is as follows:

$$\frac{\text{SiO}_2}{\text{Al}_2\text{O}_3} = \frac{8.15}{1.00}$$

$$\frac{\text{SiO}_2}{\text{BeO}} = \frac{9.10}{1.00}$$

$$\frac{\text{SiO}_2}{\text{CaO}} = \frac{9.19}{4.00}$$

As, however, the ratio of  $\text{Al}_2\text{O}_3$  to BeO is not exactly 1:1 but 1.00:0.90, it may be that the determination of beryllia is a little low and that its separation from alumina was not altogether complete. If the true content of beryllia is 0.25 per cent greater than given, namely 2.92 per cent (and the alumina correspondingly lower), then the ratio of BeO to  $\text{Al}_2\text{O}_3$  becomes 0.1168:0.1168, or exactly 1:1 and the ratio of  $\text{SiO}_2$  to  $\text{Al}_2\text{O}_3$  and to BeO becomes 8.32:1, raising doubt as to the correctness of the ratio of  $9\text{SiO}_2$ .

The analysis of bavenite from Italy is reproduced below, as given by Artini, except that his percentage of  $\text{Al}_2\text{O}_3$  has been changed, so as to allow for about the same quantity of BeO as is present in bavenite from California and to give a 1:1 ratio of  $\text{Al}_2\text{O}_3$  to BeO.

The percentage of  $\text{Al}_2\text{O}_3$  given by Artini, for the bavenite from Italy, is 15.42. Any beryllia present in the mineral would be included with the  $\text{Al}_2\text{O}_3$ . This percentage is nearly the same as that of  $\text{Al}_2\text{O}_3 + \text{BeO}$  (14.83) determined by Fairchild in the bavenite from California. As the spectrographic examination (see Fig. 4) showed that beryllium was likewise present in the bavenite from Italy, it is assumed that its percentage as beryllia is about the same as in the sample from California, namely about three. It is found by appropriate calculation that the 15.42 per cent of  $\text{Al}_2\text{O}_3$ , given by Artini, can be expressed as being composed of 12.38 per cent  $\text{Al}_2\text{O}_3 + 3.04$  per cent BeO, these values giving a 1:1 ratio of the two oxides, as was approximately found for the mineral from California. Adopting these figures and replacing Artini's determination of 15.42 per cent  $\text{Al}_2\text{O}_3$  by them, his analysis and ratios calculated therefrom, are given below.

ANALYSIS AND RATIOS OF BAVENITE FROM ITALY WITH THE  $\text{Al}_2\text{O}_3$  CHANGED TO  
ALLOW FOR THE NECESSARY BeO  
[E. Artini, analyst]

	Analysis	Ratios	
SiO <sub>2</sub> .....	56.93	.9472	8.12 or 8
Al <sub>2</sub> O <sub>3</sub> .....	12.38	.1214	1.04 or 1
BeO.....	3.04	.1216	1.04 or 1
CaO.....	24.47	.4362	} .4439    3.80 or 4
MgO.....	0.12	.0030	
Na <sub>2</sub> O.....	0.29	.0047	} .1383    1.19 or 1
H <sub>2</sub> O.....	2.49	.1383	
	99.72		

The ratios indicate the formula  $8\text{SiO}_2 \cdot \text{Al}_2\text{O}_3 \cdot \text{BeO} \cdot 4\text{CaO} \cdot \text{H}_2\text{O}$ .  
The ratios of SiO<sub>2</sub> to the bases are:

$$\frac{\text{SiO}_2}{\text{Al}_2\text{O}_3} = \frac{7.80}{1.00}$$

$$\frac{\text{SiO}_2}{\text{BeO}} = \frac{7.79}{1.00}$$

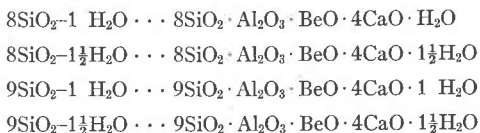
$$\frac{\text{SiO}_2}{\text{CaO}} = \frac{8.54}{4.00}$$

It is possible that in Artini's analysis, not all the silica was separated as such but part may have been included with the alumina, giving a slightly low value for SiO<sub>2</sub>. The analysis was made some 30 years ago and the 8:1 ratio of silica to alumina may be due to incomplete separation of all the silica. On the other hand, the sample of bavenite from California—compact, finely fibrous, and partly earthy—may have included in it a small quantity of free silica, such as opal or chalcedony.

The distribution of the reported percentage of Al<sub>2</sub>O<sub>3</sub> in the bavenite from Italy, between Al<sub>2</sub>O<sub>3</sub> and BeO, is of course arbitrary and the resultant ratio of SiO<sub>2</sub> to either Al<sub>2</sub>O<sub>3</sub> or BeO cannot be given too much weight in deciding the valuation of SiO<sub>2</sub> in the formula. The only base left, for such consideration, is lime, CaO. In the analysis of the bavenite from California, the ratio of SiO<sub>2</sub>:4CaO is 9.19 whereas in that from Italy, the similar ratio is 8.54, about halfway between 8 and 9.

Two formulas, with either 8 or 9SiO<sub>2</sub>, are thus indicated by the two analyses. The correct quantity of water inherently belonging to the mineral, either 1 or 1½ H<sub>2</sub>O, is also in doubt.

A comparison is therefore made between the two analyses of bavenite and the composition calculated from the four possible formulas, the ratio of SiO<sub>2</sub> and H<sub>2</sub>O being the doubtful items. The four possible formulas are:



The comparison of the two analyses with the theoretical composition, as calculated from these four formulas, is given in the following table. Each of these four formulas is indicated by the silica and water ratios.

COMPARISON OF THE TWO ANALYSES OF BAVENITE WITH THE COMPOSITION CALCULATED FROM FOUR SIMILAR FORMULAS

	Italy	California	8-1	8-1½	9-1	9-1½
SiO <sub>2</sub> . . . . .	56.93	58.40	56.55	55.96	59.42	58.84
Al <sub>2</sub> O <sub>3</sub> . . . . .	12.38	12.16	12.00	11.87	11.20	11.10
BeO . . . . .	3.04	2.67	2.94	2.91	2.75	2.72
CaO . . . . .	24.47	23.73	26.39	26.12	24.65	24.41
H <sub>2</sub> O . . . . .	2.49	2.90	2.21	3.14	1.98	2.93
MgO . . . . .	0.12	none	....	....	....	....
Na <sub>2</sub> O . . . . .	0.29	n.d.	....	....	....	....
Fe <sub>2</sub> O <sub>3</sub> . . . . .	....	0.10	....	....	....	....
	99.72	99.96	100.00	100.00	100.00	100.00

The ratio of H<sub>2</sub>O in the analysis of bavenite from Italy (1.19) is only slightly over 1 and closer to 1 than 1½. On the other hand, the ratio of H<sub>2</sub>O for the bavenite from California (1.49) is almost exactly 1½. Notwithstanding, 1H<sub>2</sub>O is chosen as correct, as it simplifies the formula of the mineral and the water content of compact fibrous minerals, as determined, is very apt to be higher than the true inherent water content. It is well known that many minerals acquire a small quantity of firmly held adsorbed water during grinding, which is retained to a very high temperature.

Both formulas with  $8\text{SiO}_2$  contain over 26 per cent of CaO, a value considerably higher than the CaO content in either analysis. The CaO content of the two formulas with  $9\text{SiO}_2$  contains a percentage value in better agreement with that found. As already stated, one part of  $\text{H}_2\text{O}$  (instead of  $1\frac{1}{2}$  parts) is chosen. The formula for bavenite is therefore given as  $9\text{SiO}_2 \cdot \text{Al}_2\text{O}_3 \cdot \text{BeO} \cdot 4\text{CaO} \cdot \text{H}_2\text{O}$ .