

Titanian taramellites in western North America

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Abstract

Taramellite, $\text{Ba}_4(\text{Fe}^{3+}, \text{Ti}^{4+}, \text{Fe}^{2+}, \text{Mg})_4(\text{B}_2\text{Si}_8\text{O}_{27})\text{O}_2\text{Cl}_x$, until recently known only at the type locality, Candoglia in Italy, has been found together with many other Ba-silicates at eight scattered localities in western North America. All of the taramellites from these localities are highly titanian and those in which Ti/Fe exceeds unity may be called titantaramellite. Contrary to the formerly current description, taramellite is not at all fibrous, but occurs in tabular to equidimensional orthorhombic crystals, in some occurrences with excellent morphology. Six of the North American occurrences are at or close to the contacts of large granitic bodies where zones or lenses within metamorphic rocks are composed largely of Ba-silicates among which sanbornite, BaSi_2O_5 , is dominant. At one locality in Santa Cruz, California, taramellite has been found in large, ragged, crystals in a metamorphosed limestone which carries a wide variety of sulfides and sulfosalts. Finally, taramellite is a minor constituent in complex veins in Franciscan enclaves within a large ultramafic body in San Benito County, California. Analyses and properties of taramellites at all eight localities are reported together with descriptions of each locality and data on the associated minerals.

Historical introduction

Taramellite was described by Tacconi (1908a, 1908b) as a new silicate of barium and iron occurring as acicular crystals or fibrous aggregates in contact metamorphosed calcareous rocks at Candoglia in the Valle del Toce, Italy. For many years thereafter no additional occurrences of taramellite were recognized as such. Montgomery (1960; Thompson and Montgomery, 1960; Montgomery et al., 1972) recognized taramellite as well as other Ba-silicates from a contact metasomatic deposit near the headwaters of the Ross River in the Yukon Territory, close to the border with the Northwest Territories. Montgomery (1960) also reported the identification of taramellite in specimens from the type locality of sanbornite in Mariposa County, California. Montgomery firmly established the identity of taramellite from Candoglia, Ross River and Mariposa County by recording closely agreeing X-ray powder patterns for each.

The first published reference to the occurrence of taramellite in California was made by Alfors et al. (1965, p. 315) in which the occurrences in Mariposa County, Fresno County, and Santa Cruz County, California, as well as that in the Yukon Territory, were mentioned.

Subsequently taramellite was recognized in a deposit of Ba-silicates in Tulare County, Calif., and in an occurrence in very limited amount with colorless benitoite in the Clear Creek area, San Benito County, California (pers. comm. E. Oylar and R. C. Erd, 1977). The presence of taramellite among numerous other Ba-silicates at the La Madrelena mine in northern Baja California had been recorded by J. R. Hinthorne (1974, p. 21). All of these eight localities were listed by Pabst (1978, Table 1).

In December of 1976 Dr. A. Kato, chairman of the I.M.A. Commission on New Minerals and Mineral Names, having noticed the high Ti content of Fresno County taramellite (as recorded by Mazzi and Rossi, 1965, footnote p. 248), wrote to one of us (A.P.) suggesting that the California taramellite should be considered "a new species as a titanium dominant member of taramellite", the original taramellite from Candoglia, Italy, being iron dominant. At the same time Dr. Kato informed us that he and Matsubara had "found a V^{3+} analogue of taramellite" in Japan which was subsequently named nagashimalite (Matsubara and Kato, 1980).

Accordingly we made a presentation to the I.M.A. Commission proposing the name titantaramellite for Ti-dominant taramellites such as some of those from Califor-

Table 1. Materials available for each locality

Number	Locality	Material
1	Ross River Yukon Territory	2 small specimens, ca. 2 and 10½ gr., gifts of the late Professor R. M. Thompson (Vancouver) 1960.
2	Trumbull Peak Mariposa County, Ca	Numerous specimens collected by A.P. 1950 and by Dr. R.M. Douglass 1953, plus commercially obtained specimens.
3	Rush Creek, Fresno County, Ca	Our own collections plus a superior specimen given by Mr. Forrest E. Cureton II of Stockton, California
4	Big Creek, Fresno County,	Our own collection plus superior specimens given by Mr. Cureton and by Mr. Robert E. Walstrom.
5	Chickencoop Canyon, Tulare County, Ca	Specimens collected by staff members of the California Division of Mines and Geology, mostly by Robert Matthews.
6	La Madrelena mine, Baja California Mexico	Three specimens provided by the late Professor E.C. Allison (1970), specimens collected by Miss Josephine L. Scripps received from W.C. Chesterman (1977) and specimens obtained from mineral dealers Si Frazier (Berkeley, 1970) and David New (Stevensville, Montana, 1974).
7	Kalkar quarry, Santa Cruz, Ca	Specimens provided by Eugene Gross (1963) and by A.P. (1964) and superior specimens provided by Mr. J.F. Cooper (Watsonville, Ca 1973) and by Mr. Gail E. Dunning (Sunnyvale, Ca 1979) plus several purchased from Minerals Unlimited (Mr. Ralph Merrill).
8	Victor Claim San Benito County, Ca Candoglia, Italy	One specimen lent by Mr. Ed Oyler (San Martin, Ca). One specimen, ca. 3½ gr., from the Museo Civico di Storia Naturale, Milano, provided by Professor F. Mazzi (Pavia) and two small specimens, 1.3 and 15.8 gr., BRGM specimen 6718 provided by Dr. J. Mantienne (Orleans, France).

nia. The new mineral and name were approved by the I.M.A. Commission in January, 1978, by votes of 18-0 and 17-1 respectively. At the suggestion of Dr. Michael Fleischer we immediately after proposed to the Commission that the new mineral be named taramellite-(Ti). This suggestion was not accepted, the vote being "Yes 4, No 5, Abstention 1."

There are now known at least ten occurrences of members of the taramellite series. They are: taramellite (Fe-dominant) at Candoglia, Italy, the type locality; nagashimalite (V-dominant) at the Mogurazawa mine, Kiryu City, Gumma Prefecture, Japan; and eight occurrences of highly titanian taramellite in western North America, some of which merit the name titantaramellite (Ti-dominant).

Material

For this study we have been able to examine specimens from all the North American localities and from Candoglia. We have collected extensively at localities 2, 3, 4 and 7 and have been able to draw upon the collections at the California Division of Mines and Geology, San Francisco, for specimens from these localities and from locality 5. Though we had ample material from locality 6 we have no personal acquaintance with this locality and specimens were obtained both from private and commercial sources. From localities 1 and 8 we had only minimal amounts of

material and from Candoglia but two small specimens. Even so, it was possible to obtain adequate amounts of taramellite from each locality for determination of composition, X-ray diffraction, some physical properties and morphology. Extensive observations on associated minerals and thin section study of the Ba-silicate rocks were carried out for all localities except 1, 8 and Candoglia. In these cases thin sections could not be used and observations on associated minerals were necessarily so limited that they may not be representative. Materials available for our study are listed in Table 1.

Chemical composition

In early analytical work on taramellite, Tacconi (1908a, 1908b), Mazzi (1957), Mazzi and Rossi (1965, footnote p. 248), Cl and B₂O₃ were not noted and, at first even titanium was not recognized. With our proposal to the I.M.A. Commission in 1977 we submitted the results recorded in column 3 of Table 2 which were based on analytical work done on Fresno County taramellite at the California Division of Mines and Geology, San Francisco, in 1965 (Table 2, col. 1) and at the U. S. Geological Survey, Washington, D. C. in 1968 (Table 2, cols. 2 and 2a); B₂O₃ and Cl being recognized as essential constituents. The formula proposed was Ba₂(Ti,Fe²⁺,Mg,Fe³⁺,Mn²⁺)₂BSi₄O₁₄(Cl,OH). Montgomery (1960) had recorded a spectroscopic analysis of taramellite in which the major elements were given as Ba, Fe, Ti, Si, the minor elements as Mg, Ca, B and the trace elements as Mn, Sn, Cu, Ag, Pb, Zn, Na and Al.

For the present study a wet chemical analysis was obtained on a 2.6 gram sample of taramellite from the Rush Creek area, Fresno County, California. This source

Table 2. Previous analyses of taramellites

	1 C.D.M.G. 1965 x-ray spec. anal.	2 U.S.G.S. 1968	2a	3 Reported to I.M.A. Comm. 1977	3a Atomic Proportions
SiO ₂		34.1		34.1	Si 16
Fe ₂ O ₃		1.2		1.2	Fe ³⁺ 0.45
FeO		4.0		4.0	Fe ²⁺ 1.57
BaO		40.8		40.8	Ba 7.50
TiO ₂		10.4		10.4	Ti 3.67
CaO		0.23		0.23	Ca 0.11
MgO		1.7		1.7	Mg 1.19
H ₂ O ⁺				0.2	
MnO	0.16-0.30	0.21	0.16	0.21	Mn 0.09
Cl	1.8			1.9	Cl 1.51
B ₂ O ₃		4.3	4.83	4.3	B 3.48
-H ₂ O		0			
Ig. loss (1000°C)		1.9			
F		0.12		0.12	F 0.18
(Al, V, Cr) ₂ O ₃		1.0		1.0	
Al ₂ O ₃			0.19		
Cr ₂ O ₃			0.15		
V ₂ O ₃		99.96	0.22	100.16	
less O/F ₂ +O/Cl ₂		-0.05		-0.48	
		99.91%		99.68%	

Column 1 Unpublished results of X-ray spectrographic determinations at C.D.M.G.

2a Values given in this column are based on values reported in ppm from emission spec. anal.; additionally found Zr 300 ppm, Sc, Sn and Sr each 200 ppm, Nb 100 ppm, Y 20 ppm.

was most advantageous for obtaining several grams of taramellite which mostly occurs as small crystals and makes up 0.1% or less of the Ba-silicate rocks. The sample was obtained by separating taramellite, which is completely impervious to attack by warm dilute HCl, from about 7 kilograms of rock in most of which the principal constituents were the acid-soluble sanbornite and quartz. The raw mineral was obtained from the copious collections from the Rush Creek area at the California Division of Mines and Geology, San Francisco, and included pieces from several outcrops or prospect pits in that area (Weiler et al., 1963), so the sample analyzed was a composite. Microprobe examination of five taramellite crystals from the Rush Creek area, three originally enclosed in sanbornite and two in quartz, showed that the compositional variation of taramellite, if any, in this area is small.

The results of this analysis as reported by Herdsman Limited, East Kilbride, are given in Table 3, column 1. Determination of total iron in the sample by Dr. M. Ghiorso and of ferrous iron by Professor I. S. E. Carmichael, performed on the remainder of the sample that had been used by Herdsman, yielded the revised values for Fe₂O₃ and FeO shown in column 1a of Table 3, leading to a rather low total. The revised values correspond fairly well to the results of several sets of microprobe analyses of Rush Creek taramellite. The low total of the revised analysis may be explained in part by the lack of determinations of Al₂O₃, Na₂O and V₂O₅ in the Herdsman analysis and the low values for MgO and Cl, possibly also for B₂O₃.

The chemical analysis reported for nagashimalite, the vanadium analogue of taramellite, is given in column 2 of

Table 3. Note that the figure for H₂O is given in brackets. Regarding this Matsubara and Kato (1980, p. 125) stated: "The wet chemical analysis proved the presence of water but the paucity of material impeded the qualitative (sic!) measurement." The figure for H₂O was evidently chosen to make Cl + (OH) = 2. Column 2b of Table 3 gives the "theoretical weight percentages" corresponding to the chosen formula. The charges balance to within 0.01 if Ti is considered tetravalent. However the percentages for B₂O₃ and Cl in column 2b exceed those given in the analysis by substantial amounts.

The formula assigned to nagashimalite was recast by Matsubara (1980) to Ba₄(V³⁺,Ti)₄[(O,OH)₂Cl][Si₈B₂O₂₇] based on the recognition of a "novel borosilicate group [Si₈B₂O₂₇]"'. A redetermination of the structure of taramellite from Candoglia and from Rush Creek by Mazzi and Rossi (1980) led to the formula Ba₄M₄(B₂Si₈O₂₇)O₂Cl_x where 0 ≤ x ≤ 1. They stated "In the Rush Creek sample the principal cation is Ti⁴⁺, in the Candoglia sample Fe³⁺" and also stated that "The best balance is obtained without H atoms, assuming 3.25+ as the charge on the Me atoms." This is in accord with the absence of H₂O shown in the new analysis of the Rush Creek taramellite. The average charge for atoms in octahedral position in nagashimalite is +3.19. If the average charge per octahedral cation is as low as +3, charge balance is maintained if x = 0. In many of the titanium-rich taramellites of western North America the average charge per octahedral cation exceeds 3.25. Such high charges for the octahedral cations can be compensated by vacancies in the boron positions as shown by charge balance for several idealized compositions.

In Table 4 are given the electron microprobe analyses of taramellite from the eight known North American occurrences and from Candoglia. B₂O₃ contents cannot be determined in such analyses. However, determinations of B₂O₃ reported in analyses previously cited are 4.3, 3.64 and 4.0 wt.% and might be as high as 4.65, the "theoretical weight percentage" given by Matsubara and Kato (1980). These values are of the right order to bring the totals for six of the microprobe analyses to values between 98 and 101%. However, three of the microprobe analyses (Victor Claim, Yukon, and Candoglia taramellites) have such low totals that even with the assumption of the maximum amount of B₂O₃ the totals would be in the range 97.5–96.7. Unfortunately the small amount of material precluded further study and the discrepancy remains.

In some samples there is great variation in the relative amounts of octahedral cations between crystals from one locality or even within one crystal. Due to the small range of variation of cell dimensions and indices of refraction (Tables 5 and 6), zoning is not readily recognized. No evidence was found for core-to-rim zoning or for sector zoning. The irregular variation of the substitution may be connected with the presence of vacancies in several positions in all analyzed taramellites. It is assumed that

Table 3. Analyses of titantaramellite and nagashimalite

	Titantaramellite Rush Creek Fresno County California		Nagashimalite Mogurazawa mine, Gumma Prefecture Japan			
	1	1a	1b	2	2a	2b
SiO ₂	33.03		8	32.37	8.00	32.10
Fe ₂ O ₃	6.79	2.03	0.37			
FeO	3.60	4.73	0.96			
MgO	0.55		0.20			
V ₂ O ₅			3.49	16.56	3.30	17.21
TiO ₂	10.63		1.94	2.75	0.51	2.99
MnO	0.09		0.02	0.48	0.10	
B ₂ O ₃	3.64		1.52	4.0	1.71	4.65
Cl	1.83		0.75	1.73	0.73	2.37
BaO	40.45		3.86	41.36	4.01	40.95
H ₂ O-	<0.01			(0.77)	1.27	0.26
H ₂ O+	<0.01					
	100.61			100.11		100.53
less O/Cl ₂	- 0.41			-0.39		- 0.53
	100.20%	96.57		99.72		100.00

Column

1 Analysis by Herdsman Limited, East Kilbride, on 2.6 gram sample.

1a Supplementary analyses on remainder of same sample by Dr. Mark Ghiorso and Professor I. S. E. Carmichael.

1b Atomic proportions on basis of Si = 8.

2 Matsubara & Kato (1980). The value for H₂O is given in brackets and in the text there is a note on the difficulty of its quantitative determination.

2a Atomic proportions on basis of Si = 8.00.

2b Theoretical weight percentages for Ba₄(V³⁺, 3.44Ti_{0.56})₄Si₈B₂O₂₈Cl₁ [(OH)_{0.44}O_{0.56}].

Table 4. Microprobe analyses of taramellites and titantaramellites from localities 1 to 8 and Candoglia

	1 Ross River Yukon Terr. Canada	2 Trumbull Pk. Mariposa County	3 Rush Creek Fresno County	4 Big Creek Fresno County	5 Chickencoop Canyon Tulare	6 Madrelena mine, Baja California	7 Kalkar Quarry, Santa Cruz County	8 Victor Claim San Benito County	Candoglia Italy
SiO ₂	32.53(50)**	34.57(61)	32.80(33)	33.38(28)	33.64(40)	33.77(40)	33.86(63)	32.75(54)	32.35(64)
Al ₂ O ₃	0.20(06)	0.17(06)	0.26(04)	0.24(06)	0.25(05)	0.23(08)	0.46(08)	0.14(05)	0.45(13)
TiO ₂	9.10(36)	10.36(28)	10.76(11)	10.49(15)	11.22(16)	9.39(19)	11.10(14)	12.53(41)	7.14(27)
FeO	7.87(30)	3.38(195)#	6.47(31)	5.97(45)	3.04(13)	4.18(165)##	3.59(34)	7.58(32)	11.61(23)
MgO	0.73(19)	3.34(123)#	1.27(13)	1.43(07)	2.19(07)	2.33(37)##	1.50(09)	0.14(04)	0.06(03)
MnO	-	0.08(02)	0.30(03)	0.06(05)	1.20(05)	0.19(09)	-	-	-
V ₂ O ₃	tr.	0.49(12)	0.37(10)	0.32(12)	0.81(07)	2.17(32)##	3.24(23)	0.09(05)	0.10(04)
Cr ₂ O ₃	0.22(07)	0.12(03)	0.02(05)	0.12(03)	-	0.66(25)	0.08(05)	-	-
BaO	39.08(08)	40.84(44)	40.73(31)	40.43(39)	40.36(06)	40.19(43)	40.48(30)	39.21(57)	39.33(39)
Cl	2.29(06)	1.77(08)	2.10(10)	2.08(04)	2.11(07)	1.86(17)	2.17(08)	0.04(03)	1.45(10)
Total*	92.02	95.12	95.08	94.51	94.82	94.97	96.48	92.48	92.49
Atoms relative to Si + Al = 16									
Si	15.89	15.91	15.85	15.87	15.86	15.87	15.75	15.92	15.74
Al	0.11	0.09	0.15	0.13	0.14	0.13	0.25	0.08	0.26
Ti	3.34	3.58	3.91	3.75	3.98	3.32	3.88	4.58	2.61
Fe	3.21	1.30	2.61	2.37	1.20	1.64	1.40	3.08	4.72
Mg	0.53	2.29	0.91	1.00	1.54	1.63	1.04	0.10	0.04
Mn		0.03	0.12	0.02	0.48	0.08	0.03		
V		0.18	0.14	0.12	0.31	0.82	1.21	0.03	0.04
Cr	0.09	0.04	0.01	0.05		0.25	0.03		
Ba	7.47	7.36	7.71	7.52	7.45	7.40	7.37	7.47	7.50
Cl	1.89	1.38	1.72	1.68	1.68	1.48	1.71	0.03	1.20
Ti+Σ	7.17	7.33	7.70	7.31	7.51	7.74	7.56	7.79	7.41
Ti/Σ	0.87	0.93	1.03	1.05	1.13	0.75	1.05	1.43	0.54

* Totals do not include B₂O₃. Values for this would lie in the range 3.64 to 4.83 of analytical results given in Tables 1 and 2, or in the range 4.55 to 4.75 indicated by calculation. See text.
 ** Also, totals would be 0.1 to 0.4 higher if part of iron were taken as Fe₂O₃.
 # The figures in brackets are the standard errors and apply to the last two or three digits.
 # The large standard errors for FeO and MgO in column 2 arise from Fe-Mg "zoning" in the taramellite from Trumbull Peak. See text.
 ## The large standard errors for FeO, MgO and V₂O₃ in column 6 arise from varying substitutions within the taramellite from the Madrelena mine. See text.

the framework of the structure is not defective, thus the number of other atoms per cell has been calculated relative to Si + Al = 16 as given in the lower part of Table 4. Ideally there should be 8 Ba per cell, whereas the analyses indicate only 7.36 to 7.71, averaging 7.47. There should also be 8 octahedral cations per cell, whereas the analyses show a range of 7.17 to 7.79, averaging 7.50.

The high values of the standard deviations for certain cations are attributable to the compositional variation just mentioned. The two most conspicuous cases are FeO and MgO in the Trumbull Peak taramellite and these two as well as V₂O₃ in the La Madrelena mine taramellite. In the Trumbull Peak taramellite MgO varies from 2.06 to 4.63% reciprocally as FeO varies from 5.25 to 1.45%, whereas TiO₂ varies only from 10.10 to 10.69%.

The deficiency of cations is not ascribable to elements not reported in Table 4. Ca is absent or below the limits of detection by the microprobe in all taramellites as are also Sn, Na and K, whereas Sr is present in the Rush Creek taramellite only in trace amount (200 ppm) as shown by emission spectroscopic analysis. Cr₂O₃ is lacking or low in all taramellites except that from Baja California. The highest V₂O₃ value, 3.24%, occurs in taramellite at the Kalkar quarry where the association is markedly different from the associations at any of the other localities.

Unit cell dimensions and structure

Unit cell dimensions of taramellite from Candoglia were reported by Mazzi (1957). The first full determination of the structure by Mazzi and Rossi (1965) was based

Table 5. Cell dimensions of members of the taramellite group

		Titanian taramellites			Titanian taramellites		
		a	b	c	a	b	c
1	Ross River, Yukon Territory	12.217(6)Å	13.954(8)	7.130(4)	7	Kalkar quarry Santa Cruz	12.149(7) 13.904(12) 7.12(2)*
2	Trumbull Peak, Mariposa County	12.202(4)	13.981(5)	7.134(3)	8	Victor Claim San Benito County	12.053(5) 13.93(2)* 7.138(3)
3	Rush Creek, Fresno County	12.184(4)	13.938(6)	7.127(3)	Taramellite		
		12.200(2)	13.952(2)	7.128(1)#	Candoglia	12.125(6) 13.929(6) 7.136(5)	
4	Big Creek, Fresno County	12.220(5)	14.005(9)	7.141(3)		12.150(3) 13.946(3) 7.129(2)#	
5	Chickencoop Canyon, Tulare County	12.199(7)	13.962(8)	7.140(4)	Nagashimalite		
6	La Madrelena mine, Baja California	12.213(4)	13.980(3)	7.136(2)	Mogurazawa mine, Japan	12.122(3) 13.937(3) 7.116(2)##	

* Values obtained from precession or oscillation patterns and having greater uncertainty.
from Mazzi & Rossi (1980, Table 1)
from Matsubara & Kato (1980)

on observations on crystals from both Candoglia and Rush Creek. At that time the presence of Cl and B in taramellite had not been established. Nevertheless, re-determination of the structure (Mazzi and Rossi, 1980), again based on material from both localities, confirmed the essential features and established the roles of Cl and B. In spite of the marked differences in composition between Candoglia and Rush Creek taramellites, differences in unit cell dimensions as well as in atomic parameters were found to be small. The Si_4O_{12} rings previously recognized are now described as components of "a borosilicate radical ($\text{B}_2\text{Si}_8\text{O}_{27}$)¹⁶⁻". The structure found for nagashimalite by Matsubara (1980) is very similar to the revised structure for taramellite reported by Mazzi and Rossi (1980).

Unit cell dimensions of members of the taramellite group found in the reports of structure determinations in 1980 are given in Table 5 together with unit cell dimensions for taramellites examined during the current study. These latter dimensions, except as noted, were all determined by the same method, using least squares procedures and only high angle $\text{CuK}\alpha_1$ reflections of quartz-calibrated zero-level Weissenberg patterns. Inspection of the total set of results shows that there is small but real variation in unit cell dimensions. Due to the small range of variation and the incompleteness of analytical data it has not been possible to establish a correlation between unit cell dimensions and composition.

Physical and optical properties and morphology

Tacconi (1908a, 1908b) reported that the indices of refraction of taramellite are >1.74 , $2E_a = 75^\circ 40'$, pleochroism is extreme, and the color for the Z direction is

nearly black. E. S. Larsen (1921, p. 141) on material from Candoglia gave the following: "Optically +, $2E = 60 \pm 5^\circ$, $2V = 40 \pm 3^\circ$ (measured), X is normal to the plates, pleochroism is marked, $\alpha = 1.770 \pm 0.003$ (pale pinkish, nearly colorless), $\beta = 1.774 \pm 0.003$ (pale pinkish, nearly colorless), $\gamma = 1.83 \pm 0.02$ (nearly opaque)."

In Table 6 are given the physical and optical properties of members of the taramellite group previously recorded and partial determinations in connection with the present study.

The remarkable pleochroism of all members of the taramellite group can be readily explained in terms of the structure. The strong absorption occurs in the a direction parallel to which lie chains of edge-shared octahedra; the sites of Ti and Fe ions and possibly other ions of variable valence between which charge transfer may occur. The chains are shown in the structure diagram by Mazzi and Rossi (1980, Fig. 1). Taramellite is a fine example of the effects of intervalence transitions in mixed-valence minerals of iron and titanium recently discussed by Burns (1981).

Tacconi (1908a, 1908b) described taramellite as being acicular and in radial fibrous aggregates. Since then it has generally but improperly been characterized as fibrous. Pabst (1978) has reported on the morphology of taramellite from all of the localities covered in the present study. In most cases taramellite occurs in well-formed crystals which may be tabular parallel to {100} to equidimensional; only pinacoidal and prismatic forms have been observed.

Description of mineral localities

The geographic distribution of six of the eight localities where highly titanian taramellites have been found is

Table 6. Density, hardness, and optical properties of members of the taramellite group

		H(Mohs)	D obs.	D calc.	α	β	γ	2V
Nagashimalite	1)	6	4.08	4.14	1.750(2)	1.750(2)	1.780(5)	
Taramellite	2)	5.5	3.923		1.763	1.770(2)		
Titanian taramellite								
1. Ross River Yukon Territory	3) 4)				1.752(2)	1.760(1)	1.770(6) _c	+77(3)°
2. Trumbull Peak Mariposa County	3)				1.747(1)	1.758(1)		
3. Rush Creek Fresno County	5)	6	4.05(2)		1.753(2)	1.757(2)	1.782(3)	45(5)°
4. Big Creek Fresno County	3) 4)		4.05(3)		1.747(2)	1.756(2)		
			4.02(5)		1.751(2)	1.761(2)		59(5)°
5. Chickencoop Canyon Tulare County	3) 4)				1.751(3)	1.757(2)	1.780(6) _c	51(2)°
6. La Madrelena mine Baja California	3) 4)				1.739(1)	1.749(2)		
7. Kalkar quarry Santa Cruz	3)		4.00(2)		1.748(2)	1.756(2) 1.752(2)		

Optical orientation is the same for all taramellites Z//a, Y//b, X//c
Pleochroism is strong in all taramellites, X=Y yellow brown, Z opaque.

- 1) from Matsubara & Kato (1980); for nagashimalite they report the same orientation as for taramellite but different colors "pleochroism strong, X = greenish yellow, Y = green, Z = greenish brown, absorption X<Y<Z."
- 2) from Tacconi (1980A), except α and β
- 3) from same specimen as microprobe analysis
- 4) from same specimen as unit cell dimensions
- 5) as reported to I.M.A. Commission

The subscript c indicates γ calculated from α , β and 2V

Entries on one line are values obtained from a single specimen. Entries on two or three lines for one locality refer to two or three specimens from that locality.

shown in Figure 1. Numbering of these localities is taken from Pabst (1978, Table 1) and is followed in Table 4 and throughout this report. Four of these localities, numbers 2 to 5, are located at or close to the contacts of large granitic bodies, as is locality 6 in Baja California. Locality 1 (also not shown on the map) lies near the headwaters of the Ross River in the extreme eastern part of Yukon Territory and is in the contact metamorphic zone adjacent to a large quartz monzonite stock. Sanbornite is the major Ba-silicate mineral at localities 1 to 6 and gillespite is prominent in all of these but locality 5 where it has not been found. Localities 7 and 8 are entirely different geologically. The Kalkar quarry (loc. 7) is in limestone of supposedly pre-Cretaceous age; the Victor claim (loc. 8) is in a small enclave of Franciscan rocks lying well within a large ultramafic body.

Table 7, amplified from Table 1 of Pabst (1978), lists minerals associated with taramellite at the eight localities in western North America and at the type locality, Candoglia, in Italy. The table is based largely on our own observations supplemented by such information as we found in the cited references. Of the Ba-silicates recorded in Table 7 all but celsian, gillespite, pellyite and bazirite, were first found in California.

1. Ross River, Yukon

The locality is at approximately 62°50' N, 130° O' W, about 8 miles west of the boundary of the Yukon Territory and the Northwest Territories, near the headwaters of the Ross River. The occurrence of Ba-silicates here was briefly reported by Thompson and Montgomery (1960, see also Montgomery, 1960). In the single specimen available to us, labelled "Gillespite, Upper Ross River," the gillespite is a granular aggregate of anhedral crystals mostly about 1–2 mm in maximum dimension. Small rough grains are embedded in the gillespite. Taramellite, which is far less abundant than the associated pyroxenes, is found in the rough grains, generally in the size range 0.1–0.3 mm. The microprobe analysis (Table 4) shows that this is to be designated titanian taramellite, not titantaramellite, as the Ti atoms do not outnumber the other atoms in octahedral coordination.

2. Trumbull Peak, Mariposa County, California

This locality became known when Rogers (1932) described the new barium silicate sanbornite. Rogers recognized gillespite, celsian, diopside, quartz, pyrrhotite and witherite among the associated minerals and reported an unknown "brown mineral with very high relief and strong absorption" which surely corresponds to taramellite.

On the north flank of Trumbull Peak, in the NE¼ of sec. 9, T.

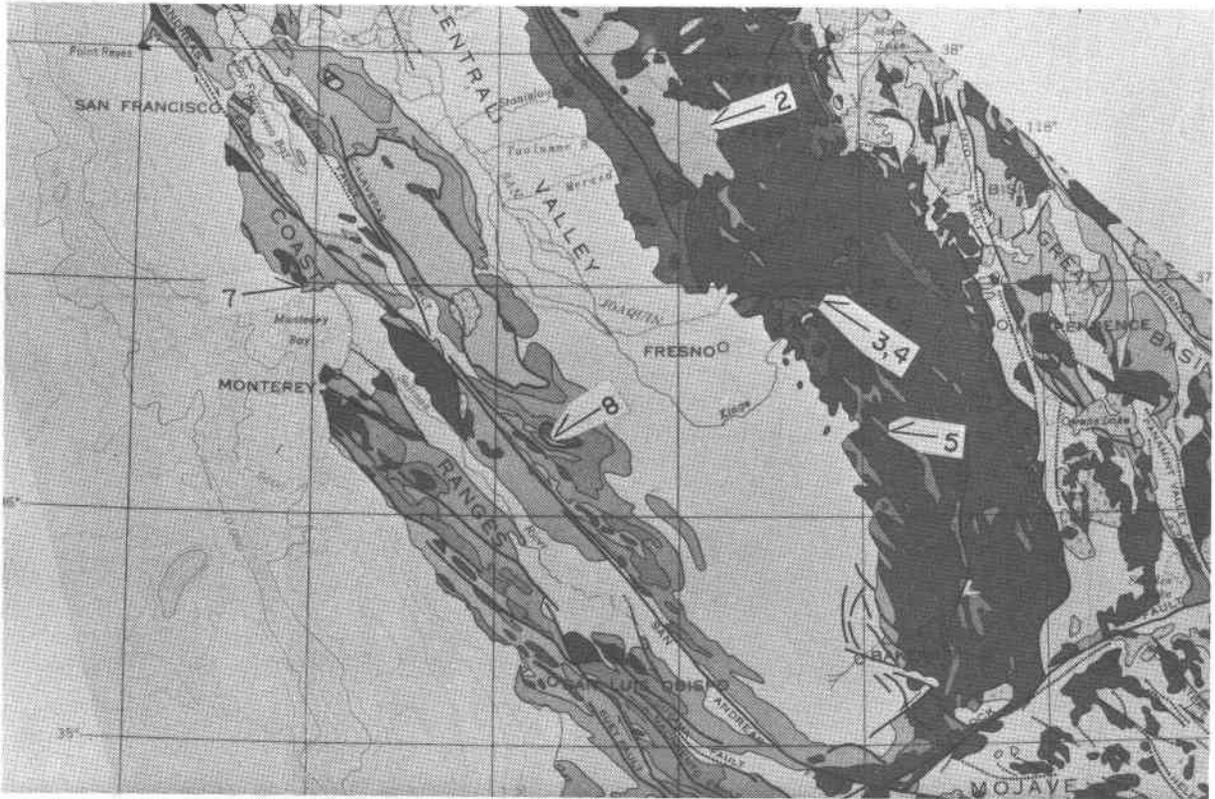


Fig. 1. Part of the geologic map of California, 1:2,500,000, showing the distribution of six Ba-silicate occurrences:- Locality 2, Trumbull Peak, Mariposa County; Loc. 3, Rush Creek, Fresno County; Loc. 4, Big Creek, Fresno County; Loc. 5, Chickencoop Canyon, Tulare County; Loc. 7, Kalkar quarry, Santa Cruz; Loc. 8, Victor Claim, San Benito County.

3 S., R. 19 E., MDBM, at an elevation of about 4,400 feet, there were three lenses, each about a meter thick and extending no more than a few meters, composed largely of sanbornite and gillespite with sharp contacts to the enclosing quartzite, part of a series mapped as Paleozoic metasedimentary rocks. The metamorphic rocks around the Ba-silicate lenses, though mostly quartzite, are partly phyllitic or hornfelsic and locally contain a little pyrite and limonite. A narrow aplite dike is only about fifty meters away but appears to have no connection with the Ba-silicates. At the time of visits in 1950 and 1953, when material used in the present study was obtained, the lenses of Ba-silicates were still intact and relations were clearly visible. Subsequently the lenses have been exploited to exhaustion.

The principal Ba-silicates found at Trumbull Peak are sanbornite and gillespite in approximately equal amount, though gillespite predominates in some specimens. These minerals together with quartz make up 95% or more of the lenses. There is a rough banding or layering in places. Bands consisting largely of quartz have a fine-grained pavement texture similar to that seen in the surrounding quartzite. This suggests that some of the quartz within the Ba-silicate rocks may be residual material from the enclosing sediments.

Taramellite is present in minor amount in every specimen examined; it is found in small, mostly ragged, crystals. Seven measured crystals, all tabular on {100}, show commonly the additional forms, {010}, {001}, {110} and {011}, less commonly the

forms {101}, {310}, {012}, and {021}. In places taramellite forms small glomeroblasts which may include pyrite.

Pellyite, hitherto known only from the type locality in Yukon Territory and from the Big Creek area in Fresno County (Montgomery et al., 1972), has been identified in several specimens from Trumbull Peak. Alforsite, the new barium chlorapatite (Newberry et al., 1981), has also been observed.

3. Rush Creek

The Rush Creek area lies in sections 9 and 16, T. 11 S., R. 25 E., MDBM, in Fresno County. The region has been geologically mapped by Macdonald (1941) on a scale of 1/62,500 and by Krauskopf (1953) on a scale of 1/125,000. As mapped by Macdonald the area lies within a body of metasediments completely surrounded by Late Jurassic biotite quartz diorite. As mapped by Krauskopf this body of metasediments lies within a migmatite zone that extends along the border of the plutonic body (designated "hornblende-biotite granodiorite") in a width of about two miles. The principal contact of the plutonic body, which is at the western edge of the Sierra Nevada batholith and here trends NNW, is a few miles south of the Rush Creek Ba-silicate occurrences.

The largest bodies of sanbornite-quartz rock occur at or close to the contacts of the metamorphic and plutonic rocks or entirely within the latter. Some of the smaller bodies of quartz-sanbornite

Table 7. Minerals associated with taramellite and titantaramellite at all known localities

	1. Ross River, Yukon Territory	2. Trumbull Peak, Mariposa County	3. Rush Creek, Fresno County	4. Big Creek, Fresno County	5. Chickencoop Canyon, Tulare County	6. La Madrelena mine, Baja California	7. Kalkar quarry, Santa Cruz	8. Victor claim, San Benito County	Candoglia
Ba-minerals									
Silicates									
sanbornite	X	X	X	X	X	X			
gillespite	X	X	X	X		X			
celsian	x	x	x	x	x	x	x		x
walstromite			x	x					
fresnoite			x	x	x			x	
verplanckite			x	x					
muirite	x		x	x					
traskite			x	x					
pellyite	x	x		x		x			
macdonaldite			x	x					
krauskopfite			x		x				
benitoite			x a					x	
pabstite							x		
bazirite				x		x r			
Non-silicates									
witherite	x	x	x	x	X	x	x		
barite	x		x b		x				
alforsite		x	x	x		x			
Other minerals									
quartz	x	X	X	X	x	x	x		
diopside-salite c	x	x	x	x	x	x	x		x
tremolite-actinolite c		x	x	x		x	x		x
sphene						x	x		x
andradite	x r								
epidote			x t						
vesuvianite		x t							
adularia								x	
pectolite								x	
calcite									x
flourapatite			x	x					
magnetite									x r
pyrrhotite		x	x	x	x	x	x		
pyrite		x	x	x	x	x	x		x
sphalerite			x	x			x		
chalcopyrite	x r								x r
arsenopyrite							x		
meneghinite							x		
References					Notes				
1. Montgomery et al. (1972)					a. stannian benitoite, Gross et al. (1965)				
2. Rogers (1932), Douglass (1958)					locality given only as "Fresno County"				
3. Weiler et al. (1963)					b. barite in part secondary				
4. Alfors et al. (1965)					c. see text for details				
6. Hinthorne (1974), Werner (1980)					r. not encountered in present study;				
7. Gross et al. (1967)					recorded on basis of literature				
8. Millage (1981)					t. trace constituent; seen but once				
Candoglia Tacconi (1908a, b)					Capital X indicates major constituent				

rock are lenses entirely within the metamorphic rocks which are mostly quartzite, relations similar to those in the Trumbull Peak area. The smaller outcrops of sanbornite-quartz rock are only about a foot wide, the largest is a tabular body 200 feet long by 30 feet wide. Two holes, 102.7 and 117.4 feet, were bored to explore the extent of these rocks (Weiler et al., 1963). The longer hole

intersected three bodies of Ba-silicate rocks, the largest is about 30 feet thick.

Taramellite in the Ba-silicate rocks may be enclosed in quartz, associated with a variety of other minerals, or embedded in sanbornite. All of the seven newly described Ba-silicates from this area and the Big Creek area (Alfors et al., 1965) are much

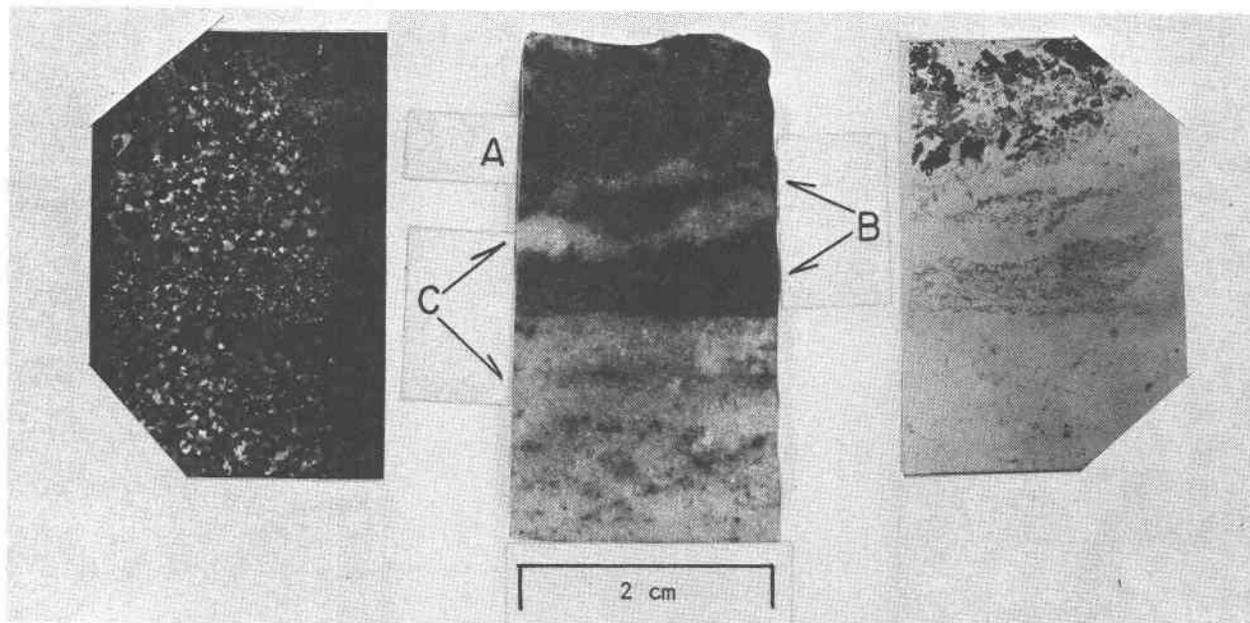


Fig. 2. Banded Ba-silicate rock, Big Creek, Fresno County, California. (Specimen, gift of F. E. Cureton) Center: Polished surface; Right: Matching thin section with crossed polars. Band A, coarse, partly poikilitic, taramellite with finer pyroxene (salite, β ca. 1.696) and colorless celsian. Band B, pyroxene with minor actinolite (β ca. 1.634) and celsian. Band C, celsian with scattered bits of salite and actinolite and a single (gray) large grain of quartz visible at lower edge of section in crossed polars.

Celsian is the principal mineral in this specimen, forming a "pavement" in thin section of bands with slightly varying, mostly very small, grain size. There is also a trace of pyrite in the specimen, not seen in the polished surface or thin section.

scarcer than taramellite and none of them have such a wide distribution. Macdonaldite, walstromite, fresnoite, verplankite, muirite, and traskite had been found in both areas in 1965, but krauskopfite was reported as limited to the Rush Creek area in the NE $\frac{1}{4}$ of Section 16. In the course of this study several minerals not previously recorded in the Ba-silicate rocks of the Rush Creek area were identified. In one specimen in which walstromite is present in abundance there are many small crystals of a light green chlorite, ripidolite, and a small amount of pellyite was identified.

4. Big Creek, Fresno County, California

The Big Creek area is in sections 22 and 27, T. 11 S., R. 25 E., MDBM, about $1\frac{1}{2}$ to $2\frac{1}{2}$ miles south of the Rush Creek area and also within the areas mapped by Macdonald (1941) and Krauskopf (1953). Along Big Creek and the Forest Service road that runs along it and on the west slope of the valley of Big Creek there are numerous isolated occurrences of sanbornite rock with many other Ba-silicates in the metasediments. These host rocks are mostly quartzite with some calc-silicate rocks, all within the zone mapped as migmatite by Krauskopf. Recently further exploration by Mr. Robert E. Walstrom in the SW $\frac{1}{4}$ of section 22 has revealed a type of Ba-silicate rocks differing from all others described in this report and limited in occurrence to a small area near the pellyite locality mentioned by Montgomery et al. (1972, p. 444). These rocks, which are free of sanbornite and gillespite, consist principally of granular celsian up to several mm in dimension in which are enclosed taramellite crystals or clusters or bands of such crystals. The largest crystals attain dimensions up to a few centimeters, larger than most occur-

rences except for those at the Kalkar quarry, locality 7. These taramellite crystals are tabular with {100} the dominant form, mostly bounded by narrow faces of {001} and other forms of the a axis zone, no other forms having been identified. Many of the taramellite crystals are poikilitic, in some cases enclosing quartz even though there is very little of this in the celsian matrix or aggregates. Examination with short-wave ultraviolet light of the rocks with celsian matrix revealed blue-white luminescent bazirite in isolated crystals or small clusters (up to 1-2 mm) in every specimen. Figure 2 shows the details of distribution of the more abundant constituents in a celsian-dominant rock with recognizable banding as seen in thin section and on a polished surface.

Gillespite is most prominent in some quartz-rich rocks with or without sanbornite in the NW $\frac{1}{4}$ of section 27. Some of this gillespite, the coarsest known, appears as ragged crystals with conspicuous cleavage up to several inches in dimension. Elsewhere in the Big Creek area there are limited exposures of Ba-silicate rocks in which sanbornite is the principal mineral but is not as coarse as in the Rush Creek area. Taramellite has been found throughout the area. Except in the celsian-rich, sanbornite-free rocks of the SW $\frac{1}{4}$ of section 22 it is always a minor, though easily recognized, constituent. Sanbornite with some fresnoite with little or no taramellite persists to the southernmost barium silicate outcrops in the vicinity of the stream-gaging station on Big Creek.

5. Chickencoop Canyon, Tulare County, California

This deposit is located at an elevation of about 1900 feet in the NW $\frac{1}{4}$, NE $\frac{1}{4}$ of Sec. 3, T. 19 S., R. 28 E., MDBM (Kaweah

Quadrangle, 1:62,500). It is about 12 miles east of Exeter on the south side of a small ravine on the northeast slope of Chicken-coop Canyon. The deposit was first mentioned by Francke (1930, p. 431) as the Baumann Ranch Barite Prospect located on the Baumann Ranch 15 miles east of Exeter. F. H. Weber, Jr., of the California Division of Mines and Geology in 1962 prepared an unpublished sketch map of the workings that consisted of four small pits, two of which contained barite. Weber did not examine the specimens collected in thin section until February, 1965, at which time he identified sanbornite and witherite in the samples. Hinthorne (1974) described the Chickencoop Canyon deposit briefly in his Ph.D. thesis.

The deposit, on the far western flank of the Sierra Nevada batholith, lies near the eastern edge of an elongate (about a half mile wide and four miles long) body of metasedimentary rocks, mainly mica schist and impure quartzite, trending northwest and completely enclosed within tonalite. The barium minerals occur in a zone in quartzite which strikes north-northwest, is about 1,000 to 1,500 feet long and varies from 1 to 5 feet in thickness. The barium mineral zone is a pale yellowish gray rock which consists principally of sanbornite and witherite with quartz. The sanbornite is altered on the outer parts of the outcrops to an opaline material. Barite occurs as cream-colored masses up to several inches thick. Hinthorne (1974) also noted taramellite and fresnoite in samples from the deposit.

Taramellite was found in each of the five specimens examined. Except for the lack of gillespite¹ the principal associated minerals are the same as those at localities 2, 3, 4 and 6 (see Table 7) but vary greatly from one specimen to another. Thin veins of quartz and krauskopfite, previously recognized only in the Rush Creek deposits, were found in two specimens from locality 5. Witherite is a major constituent of several of the specimens from this locality, but celsian, omnipresent in the other Sierran barium-silicate deposits and a major constituent in places, is inconspicuous in the Chickencoop Canyon rocks and lacking in some of them.

6. La Madrelena mine, Baja California, Mexico

The locality is a small prospect designated "La Madrelena (Cobalto) (Abandonado)" on the Mexican topographic map, 1/50,000, about 4 km east of Tres Pozos, at about 32° 22' N, 116° 3' W in northern Baja California. The general geology of the area has been mapped in reconnaissance on a scale of 2/250,000 by Gastil et al. (1975). The La Madrelena mine is at the western edge of a large plutonic body mapped as granodiorite which makes up most of the Sierra Juarez. This is part of the Mesozoic batholith of Southern and Lower California (Larsen, 1948, p. 135, Fig. 3). The locality has been briefly described by Hinthorne (1974, pp. 20-28) who wrote "The sanbornite-quartz rocks occur here as a bed in the metasedimentary sequence and in some places are only a few meters from the sharp contact of metamorphic and plutonic rocks. The pendant rocks immediately adjacent to the sanbornite bed are impure metasedimentary quartzites, schists and minor calc-silicates."

The local geology has been described in more detail by Werner (1980) who provided a geologic map and cross section of the immediate surroundings of the La Madrelena mine on a scale of 1/2,000. The map shows a group of small pendants of metasedi-

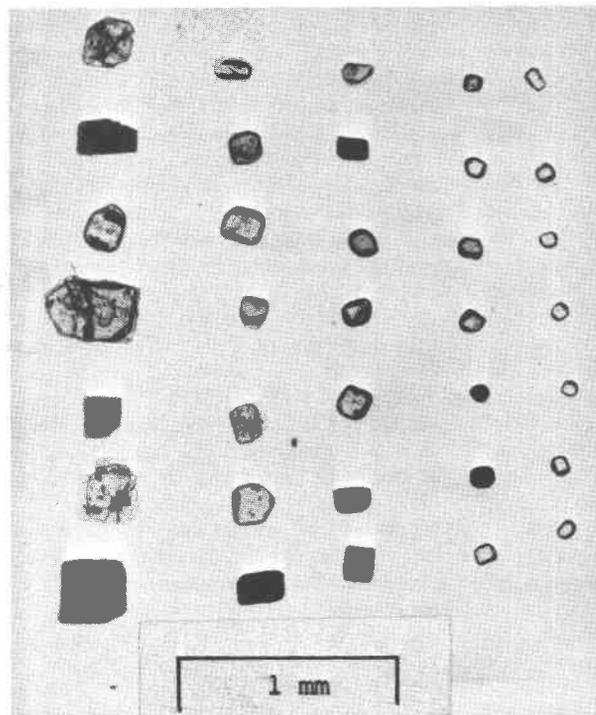


Fig. 3. Typical small euhedral taramellite crystals isolated from Ba-silicates rock. La Madrelena mine. Baja California. Largest crystal *ca.* 0.4 mm, smallest *ca.* 0.05 mm.

ments trending NNW, surrounded by tonalite and associated with granite pegmatite. The La Madrelena mine is a small pit about 2 × 3 m and 3 m deep at the western contact of one of the pendants where tonalite, quartzite, tremolite schist and the Ba-silicate rocks in which sanbornite is the principal constituent are exposed.

All of our specimens from the La Madrelena mine, which were obtained from four different collectors or suppliers, are remarkably similar. Sanbornite is the principal mineral in all specimens, some crystals attaining dimensions of *ca.* 2 cm; finer grained where mixed with quartz or in quartzite. Gillespite in elongated aggregates surrounded by sanbornite is most conspicuous and may also reach 2 cm in dimension. The sanbornite is invariably altered to a depth of 2 to 3 cm at those surfaces of the specimens which have been exposed. The many minor constituents of the Ba-silicate rocks are generally identifiable only with the microscope but in some places taramellite is easily recognized by eye embedded in the leached sanbornite. The taramellite is in very small, but perfectly euhedral, tabular crystals (Fig. 3).

7. Kalkar quarry Santa Cruz, California

The quarry is located in the SW¼, Sec. 11, T. 11 S., R. 2 W., MDBM, at the west end of Spring Street in the City of Santa Cruz. It is in an area mapped as "Pre-Franciscan limestone (?)" on the areal geology map in the Santa Cruz Folio (no. 163) of the U. S. Geological Survey (Branner et al., 1909). A. A. Fitch (1931, p. 8), referring to this quarry, stated that "Irregular beds of limestone are converted more or less completely, into aggregates of quartz, diopside, forsterite, phlogopite, titanite, tourma-

¹ The listing of gillespite as an associated mineral at this locality by Pabst (1978, Table 1) was erroneous.

line, chlorite, arsenopyrite and pyrite. . . ." He also stated that "The sedimentary series is to be correlated with the Sur Series of Trask (1926)." Branner et al. as well as Fitch attributed the metamorphism of the limestone to the effect of the nearby quartz diorite which forms the core of Ben Lomond to the northwest.

Limestone had been quarried at many points in the area and in 1922 the Pacific Limestone Products Company took over a small existing quarry and operated it for forty years to produce a variety of limestone products. During this period several mineral collectors noticed sulfosalts and other minerals overlooked by Fitch. Finally a comprehensive account of the mineralogy of the quarry was published by Gross et al. (1967). They listed over fifty species occurring in the quarry, including all those mentioned by Fitch. Among the 50 minerals are 13 sulfides, 5 sulfosalts and one oxy-sulfide, kermesite.

This varied association in a metamorphosed limestone invites comparison with the association in rocks of a similar age at the famous Lengenbach locality in Switzerland, for which a recent listing (Graeser, 1977) includes 10 sulfides and 28 sulfosalts. Of the sulfides only 6 (chalcopyrite, galena, molybdenite, pyrite, sphalerite and arsenopyrite and of the sulfosalts only two (boulangerite and tetrahedrite) are common to the two localities.

Barium-bearing minerals recognized at Kalkar are: taramellite, celsian, pabstite and witherite. The tin-bearing minerals are: stannite, franckeite ($Pb_5Sn_3Sb_2S_{14}$), cassiterite and pabstite. The distribution of minerals in the quarry is most irregular. Gross et al. (1967, p. 10) have estimated that the temperature of mineral formation ranged from above 600°C to below 400°C. Taramellite and pabstite are limited in their occurrence to a small area, taramellite has not been found in place, but only in piles of rock on the quarry floor (Dunning, pers. comm. 1979 & 1981). Quarry operations ceased over 15 years ago and "development" is planned, so that further field studies will probably be impossible.

Taramellite at the Kalkar quarry appears in crystals up to 2-3 inches long, far larger than at any other locality (Fig. 4). However, the crystals are anhedral and mostly intergrown with tremolite so that they often appear fibrous as does the taramellite from the type locality. Nearly pure diopside is more abundant than tremolite in the Kalkar rocks but is not intergrown with taramellite. Specimens containing taramellite invariably also contain pabstite. Meneghinite and arsenopyrite are commonly seen with taramellite.

8. Victor claim, San Benito County, California

The Victor claim is located in the SE $\frac{1}{4}$, SW $\frac{1}{4}$, sec. 7 T. 18 S., R. 12 E., MDBM, at an elevation of ca. 3,600 feet on a small tributary of Clear Creek, ca. 120° 42' W, 36° 22' N (San Benito Mtn. quadrangle, 1/24,000, New Idria quadrangle, 1/62,500). The locality is within a large body of ultramafic rocks on the border between San Benito and Fresno Counties in the southern part of the Diablo Range of the California Coast Ranges. Within this ultramafic body are enclosed several slabs of metamorphosed Franciscan rocks up to half a mile long. The area of the ultramafic body occupies most of the geologic map of the New Idria District, 1/48,000, of Eckel & Myers (1946). Some of the large slabs of Franciscan metamorphic rocks surrounded by serpentine are shown on this map, but many more, including the one in which the Victor claim is located, had not been noticed or recorded in 1946. Ba-silicate minerals occur in veins in several of the bodies of Franciscan metamorphic rocks within the ultramafic mass. The first recognized and best described occurrence is at the Benitoite Gem mine (Louderback, 1909; Wise & Gill,

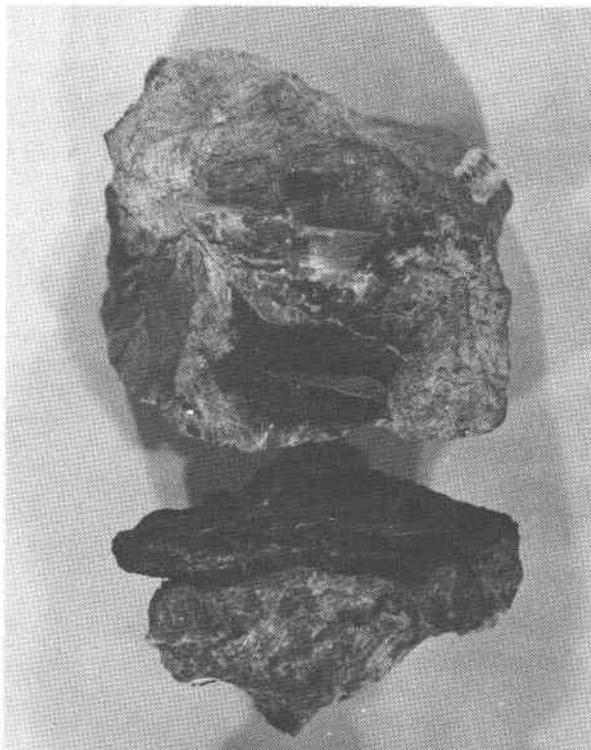


Fig. 4. Taramellite in metamorphosed limestone, Kalkar quarry, Santa Cruz, California. Natural size. Larger piece is gift of Gail E. Dunning, 1979; smaller piece purchased from MINERALS UNLIMITED, 1979.

1977). It is the type locality for the rare Ba-silicates benitoite, joaquinite and jonesite. Recently cymrite and banalsite have been recognized in a jadeitic tectonite inclusion along Clear Creek in the area where large masses of pure jadeite were described by Yoder and Chesterman (1951).

Benitoite at the Victor claim is colorless and the crystals are small, hexagonal, platelets no more than a few millimeters in dimension and markedly different from the blue benitoite crystals of trigonal habit at the Benitoite Gem mine. The small colorless plates are most easily recognized by their pale bluish white fluorescence in short-wave ultraviolet light. At the Victor claim three other Ba silicates, joaquinite, fresnoite and taramellite, have been identified among the vein minerals (Millage, 1981). Millage also lists albite, apatite, parawollastonite and adularia among the vein minerals. Taramellite is by far the rarest of all these minerals at the Victor claim. The Victor claim taramellite differs from all the other taramellites here described in that it occurs as free-standing crystals rather than being embedded in sanbornite or quartz.

Candoglia, Italy

According to Tacconi (1908a, 1908b) taramellite occurs at Candoglia in marble at its contact with gneiss. The associated minerals were listed as calcite, magnetite, chalcopyrite, pyrite, diopside, pyroxene, actinolite and celsian. The white part of specimen No. 6718, labelled "Celsian, Candoglia (Italy)," is mostly calcite, the dark part mostly green amphibole. Other

minerals identified in approximate order of abundance are: pyroxene, pyrite in tiny faceted crystals, witherite and celsian. The specimen from the Milano museum consists mostly of taramellite intergrown with amphibole as described by Tacconi, with minor amounts of calcite, witherite and celsian.

Minerals associated with taramellites

Sanbornite

Sanbornite is a major component of the Ba-silicate assemblages at localities 1 to 6, all of which are located at or near the fringes of large granitic intrusives, but has not been found in any other situation. It is invariably associated with witherite and taramellite. Except for variations in crystal size and extent of leaching, sanbornite is remarkably constant in properties. The coarse sanbornite crystals commonly enclose other minerals, in the Rush Creek area especially taramellite and pyrrhotite. The best euhedral crystals of taramellite were obtained from naturally or artificially leached sanbornite.

Gillespite

Gillespite, $\text{BaFeSi}_4\text{O}_{10}$, is found with sanbornite at localities 1 to 4 and 6, being the major mineral in the Trumbull Peak deposits, and reaching its best development in places along Big Creek where ragged crystals with excellent cleavage, embedded in quartz, attain dimensions of 6 cm or more.

Celsian

This barium feldspar is present in all localities, 1 to 6, where sanbornite and taramellite occur. It is also associated with taramellite at the Kalkar quarry and at Candoglia where sanbornite is lacking. Cymrite, $\text{BaAl}_2\text{Si}_2\text{O}_8 \cdot \text{H}_2\text{O}$, (Essene, 1967) may be considered to be the high-pressure counterpart of celsian in the Franciscan terrane or in Franciscan enclaves in ultramafic rocks (Pabst, 1977, Table 3) where it is associated with jadeite or lawsonite and other minerals under metamorphic conditions of high pressure and relatively low temperature.

In all places where celsian occurs with taramellite it is found in very small crystals, often enclosed in quartz. If present in abundance celsian may form hard saccharoidal aggregates with quartz, but the celsian-dominant rocks in a small part of the Big Creek area contain very little quartz. In some samples the celsian has anomalous optical properties and a much smaller $2V$ than previously reported.

Macdonaldite, krauskopfite, walstromite, fresnoite, verplanckite, muirite and traskite

These seven minerals, described together from the Rush Creek and Big Creek areas (Alfors et al., 1965) must be considered in two groups. Macdonaldite, $\text{BaCa}_4\text{H}_2\text{Si}_{16}\text{O}_{38} \cdot (8+x)\text{H}_2\text{O}$ with $x = 2.4$ (Cannillo et al., 1968, p. 412), and krauskopfite, $\text{Ba}[\text{Si}_2\text{O}_4(\text{OH})] \cdot 2\text{H}_2\text{O}$ (Coda et al., 1967), are secondary minerals occurring in veinlets or

lining cracks in the Ba-silicate rocks. They formed after, not with, taramellite. Macdonaldite was reported to be ubiquitous in the Rush Creek and Big Creek areas and was also found in specimens from Trumbull Peak, whereas krauskopfite was found only in a small section of the Rush Creek area (Alfors et al., 1965, p. 318). Krauskopfite has now been identified in specimens from the Chickencoop Canyon deposit, in very thin, fine-grained, veins or coatings similar to those in the Rush Creek rocks. No additional occurrences of macdonaldite have been noted.

Fresnoite, $\text{Ba}_2(\text{TiO})[\text{Si}_2\text{O}_7]$, is rather conspicuous in some specimens from the Chickencoop Canyon locality; Hinthorne (1974) also noted its occurrence there. It is easily recognized by its high refractive indices and anomalous blue interference colors. Muirite, which is locally abundant in section 27 in the Big Creek area, is also present in the Ross River rocks. It was designated mineral E by Montgomery (1960, Table 10 and Plates VII & VIII) whose report of the powder diffraction pattern, pleochroism, and semiquantitative emission spectrographic analysis leave no doubt as to its identity. No additional occurrences of walstromite, traskite and verplanckite have been noted during the current study. Of these three minerals walstromite is surely the most abundant, being a major constituent in some of the Big Creek and Rush Creek rocks with crystals up to 1 cm in size as emphasized by Hinthorne (1974, p. 19). All of the "Seven new barium minerals" are usually far less abundant and less widespread than taramellite with which they are invariably associated. Walstromite is more abundant than taramellite in the few places where it is a major constituent.

Benitoite group minerals

The isostructural minerals of this group are: benitoite, $\text{BaTiSi}_3\text{O}_9$, pabstite, $\text{BaSnSi}_3\text{O}_9$ (Gross et al., 1965) and bazirite, $\text{BaZrSi}_3\text{O}_9$ (Young et al., 1978). Stannian benitoite with up to 4.1% SnO_2 has been reported from a drill core in the Rush Creek area (Gross et al., 1965, p. 1167). Hinthorne (1974, p. 25–26, Table 2) reported the occurrence of small grains of what he referred to as "zirconian pabstite" in a "small dike" at the La Madrelena mine which is free of sanbornite but carries taramellite and celsian. Two compositional variants were reported with the tetravalent cations in octahedral coordination ($\text{Zr}_{0.90}\text{Sn}_{0.03}\text{Ti}_{0.07}$) and ($\text{Zr}_{0.42}\text{Sn}_{0.40}\text{Ti}_{0.18}$). The first should obviously be designated bazirite; the second might be designated stannian bazirite.

The bazirite which is scattered as tiny specks in the celsian-dominant rocks of the SW $\frac{1}{4}$ of section 22 in the Big Creek area occurs in thin basal plates about 0.1 mm thick and up to 0.25 mm wide. Most are ragged, but a few have measurable $\{0001\}$ and $\{10\bar{1}0\}$ forms. Many platelets tested conoscopically yielded centered uniaxial positive interference figures indicating low birefringence. Indices of refraction for one such crystal were found to be ω

1.679(1) and ϵ 1.688(2) and the unit cell dimensions are a 6.737(4) and c 9.997(6) Å, close to the values reported for the Zr end-member. The birefringence is less than expected and may indicate a substantial Sn content. Colorless benitoite with prominent basal faces is the major mineral lining the narrow open cracks in some parts of the Victor claim. Pabstite is a constant associate of taramellite at the Kalkar quarry.

Pellyite

Pellyite, $\text{Ba}_2\text{Ca}(\text{Fe},\text{Mg})_2\text{Si}_6\text{O}_{17}$, was recognized as a new mineral in the Ross River area by Montgomery (1960) and later in specimens from the Big Creek area (Montgomery et al., 1972, p. 444). It has also been found in the Ba-silicate rocks of the Trumbull Peak area and the La Madrelena mine.

Barite

A substantial amount of barite was penetrated by a bore hole in the Rush Creek area (Weiler et al., 1963) and is associated with sanbornite, taramellite and other barium minerals. In the Rush Creek area it was also observed occurring as a secondary mineral adjacent to Ba-silicate outcrops where it was obviously formed by the action of sulfuric acid derived by oxidation of iron sulfides. It was also recorded from the Ross River locality (Montgomery et al., 1972, p. 444) and at the Chickencoop Canyon locality where barite had been reported (Francke, 1930).

Witherite

This barium carbonate is associated with taramellite and other Ba-silicates at all localities here considered except the Victor claim. At the Kalkar quarry and Candoglia it occurs with calcite. At Ross River Montgomery (1960, p. 28) found a mixture of alstonite, $\text{BaCa}(\text{CO}_3)_2$, and its dimorph, barytoalcite, as a white incrustation on some specimens. At the five other closely related occurrences witherite is the only carbonate that has been recognized. Most concentrates of sanbornite are contaminated with witherite. The witherite is probably in part secondary, being present in small aggregates along cracks or veinlets in partly altered sanbornite or in other Ba-silicates. However, in some places it is a major constituent as at Rush Creek where it has been observed intimately mixed with walstromite. It is most abundant at the Chickencoop Canyon locality where parts of the deposit are made up of fairly coarse-grained (5–10 mm) witherite rock enclosing taramellite, fresnoite, partly altered sanbornite, and pyrrhotite. The rock is traversed by veinlets of krauskopfite and by zones of microbrecciation showing that alteration and deformation modified the rock after the formation of its main constituent, witherite.

Alforsite

This new mineral, $\text{Ba}_5(\text{PO}_4)_3\text{Cl}$, the barium analogue of chlorapatite, was detected by Eric Essene in specimens

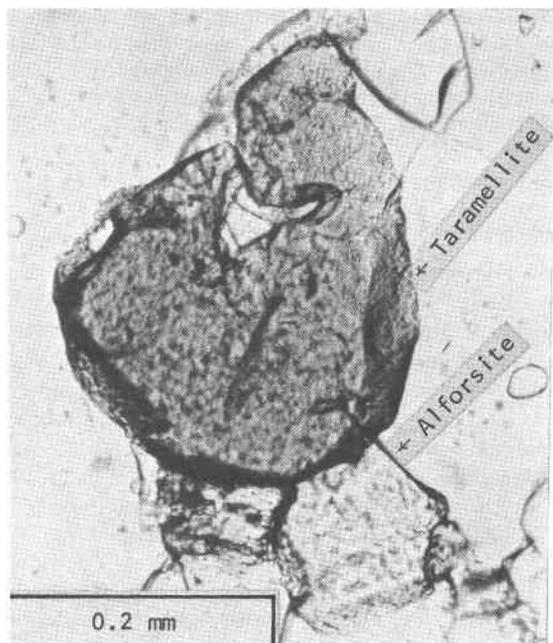


Fig. 5. Alforsite adjoining taramellite in quartz. Tiny rounded grains in quartz are celsian. La Madrelena mine, Baja, California.

from the Big Creek area and was described by Newberry et al. (1981) who also reported finding it in specimens from the Trumbull Peak locality. In connection with the present study alforsite has also been found at the Rush Creek locality and the La Madrelena mine (Stinson, 1982), where it is especially abundant. In thin section it is seen as scattered anhedral grains, never exceeding 0.2 mm in width, embedded in quartz and, sometimes, in contact with taramellite (Fig. 5).

Pyroxene

Members of the diopside–hedenbergite series are ubiquitous in the Ba-silicate rocks at localities 1 to 6 and at the Kalkar quarry, but are lacking at the Victor claim where the veins are free of pyroxene though jadeite is a major constituent of some of the nearby metamorphic rocks.

Amphiboles

Members of the tremolite–actinolite series are present in some specimens from each of the localities (2, 3, 4 and 6) in which sanbornite and/or gillespite are the dominant silicates. In each case they occur together with Fe-poor pyroxenes which are usually more abundant. At Candoglia and at the Kalkar quarry the anhedral taramellite is intergrown with ferroactinolite and tremolite, respectively.

Titanite

Titanite in very small crystals with β near 1.90 is associated with calcite, pyroxene, pyrite and celsian in

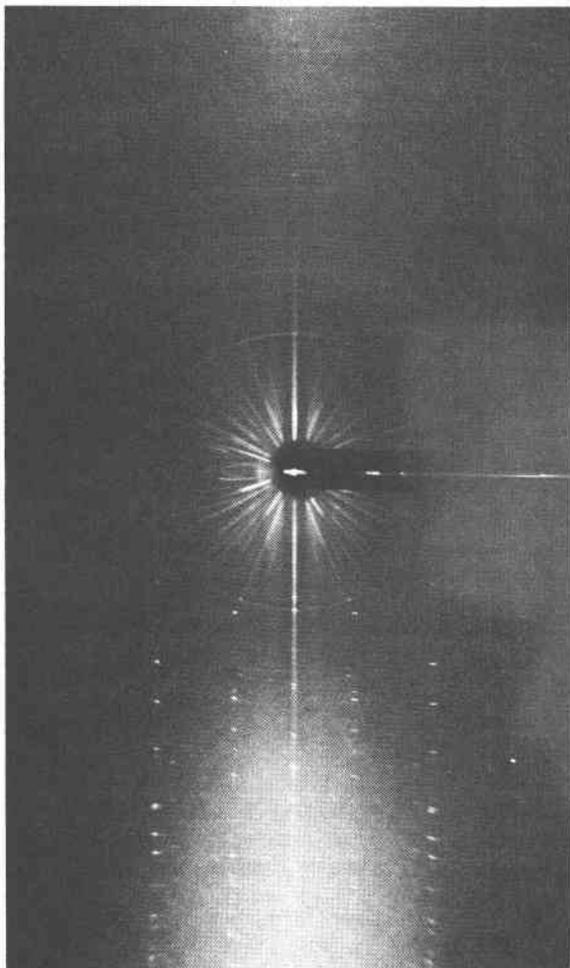


Fig. 6. *c*-axis 180° oscillation pattern of taramellite after 24 hours at 960° C showing powder arcs of newly formed fresnoite. Fe radiation, no filter, 22 hours exposure.

the small BRGM No. 6718 specimen from Candoglia labelled "Celsian." At the Kalkar quarry titanite, though inconspicuous in hand specimen, is readily recognized in concentrates from the rocks carrying taramellite. It is in small (under 1 mm) crystals with the common wedge-like habit and α is near 1.90.

Chlorite

Minerals of the chlorite group have been noted in the Ba-silicate rocks only in one specimen each from Trumbull Peak and from Rush Creek and so must be considered very minor associates of taramellite.

Vesuvianite

A very small amount of vesuvianite was isolated from a single specimen representing just one of the three lenses of Ba-silicate rocks at Trumbull Peak. This vesuvianite is

colorless, has extremely low birefringence and mean index close to 1.70 indicating low iron content; its cell dimensions are a 15.54(1), c 11.86(5)Å.

Pyrrhotite and pyrite

Pyrrhotite or pyrite or both are present as isolated grains embedded in sanbornite or interstitial among other constituents in all taramellite-bearing specimens from localities 2 to 6. In one specimen from the Big Creek area pyrrhotite and pyrite occur together, the former being far more abundant. This pyrrhotite was found to be hexagonal with a 3.450(4) and c 5.735(5)Å. The spacing of $10\bar{1}2 = 2.068$ indicates a metal content of 47.5 atomic % according to Arnold and Reichen (1962, Fig. 1). This, in turn, suggests a temperature of formation of the coexisting sulfides of the order of 300°C; see, for instance, Craig and Scott (1974, Fig. CS-11).

Sphalerite

Weiler et al. (1963, p. 9) recorded sphalerite among the sulfides occurring at the Rush Creek Ba-silicates locality. In the course of the present study it has also been found in the Big Creek area. It is invariably black and opaque. The unit cell edge of 5.423(9)Å determined for the Big Creek sphalerite and 5.423(2)Å for that from Rush Creek suggest a rather high iron content.

Effect of heat on taramellite

All observations were made on taramellite selected from the same source as the analytical sample (Table 3, column 1). One test crystal weighing 3.00 mg, several slivers, and smaller control crystals were incrementally heated in air at 100°C and in 16 steps to 940°C, the final steps being 36 hours at $920 \pm 10^\circ\text{C}$ and 6 hours at $960 \pm 10^\circ\text{C}$. After each heating, usually for about 36 hours, the test crystal was weighed and smaller crystals or fragments examined optically and by X-ray diffraction.

In summary: (1) Taramellite suffers no weight loss on heating to 920°C. (2) No melting is recognized at 885°C; incipient melting is recognized at 920°C, but even after 27 hours at 965° taramellite is not fully melted. (3) The dulling of crystal surfaces and beginning murkiness of the initially clear crystals after serial heating to 765° C is probably attributable to the beginning of formation of fresnoite even though diffraction effects due to fresnoite are readily recognized only at somewhat higher temperatures. (4) At 960°C fresnoite is formed in abundance both in the unchanged taramellite and in the newly formed glass of index 1.694 (Fig. 6.).

Epilogue

At the time of the initial studies on the sanbornite deposits in Fresno County a list of about 20 unknown minerals from these localities was drawn up. Seven of these minerals were described and named by Alfors et al.

(1965). In the course of the present studies additional occurrences of several rare barium minerals, including pellyite, alforsite, bazirite and anadite, a rare Ba brittle mica (Pattiarchi et al., 1967; Giuseppetti et al., 1972) found as an alteration product of gillespite in the Big Creek area, have been recognized. It seems probable that there are several more new minerals among the unknowns. Preliminary X-ray and optical observations have been made on a few but chemical data are lacking. We are informed that Dr. D. Appleman of the U. S. National Museum is examining some new minerals from the Basilicate deposits supplied by Mr. R. E. Walstrom.

There may even be problems with some of the Basilicates that have been fully described. Four different formulas, differing only slightly, have been assigned to muirite, the first (Alfors et al., 1965), soon modified on the basis of a revised analysis (Alfors and Putman, 1965), and two by Khan & Baur (1971) and by Malinovskii et al., (1975). A recent microprobe analysis of supposed muirite, selected optically, yielded an anomalously high Cl content. Obviously, more work is required, especially microprobe analysis of crystals characterized by single-crystal X-ray diffraction.

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