

TAVORITE AND BARBOSALITE, TWO NEW PHOSPHATE MINERALS FROM MINAS GERAIS, BRAZIL*

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ABSTRACT

Two more new phosphate minerals—tavorite and barbosalite—have been discovered in the Sapucaia pegmatite mine in Minas Gerais, Brazil. Three other minerals recently described were named frondelite, faheyite, and moraesite. The Sapucaia pegmatite is granitic in composition, is zoned on the basis of texture and mineral composition, and has had a significant production of muscovite and beryl.

Tavorite and barbosalite are intimately intergrown secondary phosphate minerals that occur with many other phosphate minerals in the pegmatite, such as heterosite, ferrisicklerite, hureaulite, vivianite, strengite, metastrengite, childrenite, variscite, frondelite, faheyite, moraesite, triphylite, montebrasite, roscherite, and apatite. Other accessory minerals are spodumene, beryl, tourmaline, and sulfides. Quartz, perthite, albite, and muscovite are the essential minerals of the rock.

Tavorite is a hydrous lithium ferric phosphate, the ferric analogue of montebrasite with which it is isostructural. It is named in honor of Dr. Elysairio Tavora, Professor of Mineralogy, Universidade do Brazil, Rio de Janeiro. The mineral occurs as a yellow, very fine grained aggregate with a mean index of refraction of 1.807 and a specific gravity of 3.29. The chemical analysis shows the following percentages: Li_2O 7.64, FeO 2.39, MnO 1.47, Fe_2O_3 42.57, P_2O_5 39.78, H_2O^+ 5.76, and H_2O^- 0.40. The formula, as derived from the chemical analysis, is $(\text{Li}_{0.90}, \text{Fe}''_{0.96}, \text{Mn}''_{0.04}) \text{Fe}'''_{0.94}(\text{PO}_4)_{0.99}(\text{OH})_{1.13}$ as compared with the ideal formula $\text{LiFe}(\text{PO}_4)(\text{OH})$. X-ray powder data show principal d -spacing (in Å) at 3.045, 3.285, 4.99, 4.68, and 2.474.

Barbosalite is a hydrous ferrous ferric phosphate, the ferric analogue of scorzalite. It is named in honor of A. L. de M. Barbosa, Professor of Geology, Escola de Minas, Minas Gerais, Brazil. The mineral occurs in black nearly opaque grains and masses. Thin grain edges are dark blue green with evident pleochroism. The approximate indices of refraction are: $\alpha=1.77$ and $\gamma=1.835$ and the specific gravity is 3.60. The chemical analysis, recalculated to 100 per cent after subtracting admixed tavorite, is: FeO 13.10, MnO 2.82, Fe_2O_3 41.65, P_2O_5 37.50, and H_2O 4.93 per cent. Its ideal chemical formula is $\text{Fe}''\text{Fe}'''_2(\text{PO}_4)_2(\text{OH})_2$. X-ray powder data indicate principal d -spacings (in Å) at 3.361, 3.313, 4.84, 3.239, 3.160, and 2.327. The mineral is structurally identical with a synthesized compound described by Gheith as ferrous ferric lazulite and both are closely related to, but have larger cell size than, scorzalite.

Tavorite and barbosalite are examples of complete substitution of trivalent iron for aluminum in known mineral structures.

INTRODUCTION

Tavorite and barbosalite are two new phosphate minerals from the Sapucaia pegmatite mine, Minas Gerais, Brazil. Three others—frondelite, faheyite, and moraesite—have been described in earlier issues of this journal (Lindberg, 1949; Lindberg and Murata, 1953; and Lind-

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berg, Pecora, and Barbosa, 1953). These accounts are preliminary to a more detailed description, in preparation, of the mineralogy and structure of the pegmatite. A summary of the present paper was published in *Science* (Lindberg and Pecora, 1954).

The Sapucaia pegmatite mine is in the municipio of Galilea, formerly a part of Conselheiro Pena, in the Rio Doce valley region in eastern Minas Gerais. This mine, a substantial producer of mica and beryl, was mapped and studied in the period 1943–1945 by Messrs. Pecora and Barbosa, participants in a joint field program of pegmatite investigations in Brazil by the U. S. Geological Survey and the Departamento Nacional da Produção Mineral (D.N.P.M.) of Brazil. Suites of mineral specimens collected during those visits were examined in Rio de Janeiro and later were turned over to Mrs. Lindberg for a more detailed mineralogical study. The original collections were augmented by additions in 1950–1953 from other sources. Type material of both tavorite and barbosalite have been deposited with the U. S. National Museum, Washington, D. C. (U.S.N.M. 106, 842) and with the Museu Nacional of the D.N.P.M., Rio de Janeiro.

GEOLOGIC RELATIONS

The granitic pegmatite at the Sapucaia mine is oval shaped in plan and internally well zoned (Pecora, et al., 1950, p. 254). The essential minerals are quartz, perthite, muscovite, and beryl. Phosphate minerals are abundant in the central part of the pegmatite. Several tons of discarded phosphate material are scattered in the mine waste of the dump.

Triphylite is the principal phosphate mineral, and heterosite is its chief alteration product. Other phosphate minerals, in addition to tavorite and barbosalite, are frondelite, hureaulite, vivianite, faheyite, childrenite, apatite, roscherite, strengite, metastrengite, variscite, ferrisicklerite, montebrasite, and moraesite.

The central part of the pegmatite, where open-pit operations are conducted for recovery of beryl, is essentially composed of giant-sized perthite masses containing numerous irregular books of "reeved" and "fish-tailed," light-colored muscovite; an irregular framework of quartz; several elongate, fluted masses of beryl; and a ramiform veinlike mass of triphylite that is intricately veined by dark purple heterosite. Several minerals locally intergrown with unaltered triphylite are quartz, muscovite, albite, sphalerite and other sulfides, tourmaline, and montebrasite.

The alteration of triphylite is characterized by the formation of heterosite and many other secondary phosphate minerals. It has not yet been established which minerals were formed by hydrothermal alteration and which by weathering. The principal feature of the alteration is a

crude mineral zoning, well demonstrated by abundant hand specimens and illustrated schematically in Fig. 1. Massive, unaltered triphylite is separated from massive heterosite and ferrisicklerite by a porous, altered triphylite zone whose spongelike cavities contain terminated crystals of colorless hureaulite, crystalline aggregates of blue vivianite, and crystalline aggregates of black barbosalite. Most of the barbosalite and tavorite, however, is found in a zone between the heterosite and porous

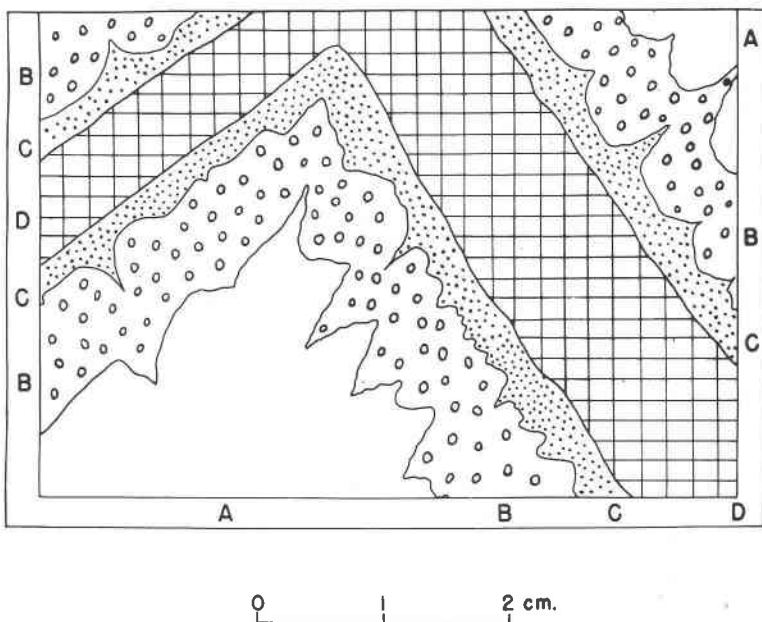


FIG. 1. Idealized sketch showing zones of secondary phosphate minerals in triphylite. *A*, unaltered triphylite; *B*, porous, altered triphylite with cavities containing colorless hureaulite crystals, crystalline aggregates of blue vivianite, and crystalline aggregates of black barbosalite; *C*, fine-grained blue-green zone containing essentially black barbosalite, yellow tavorite, and intermediate alteration products; *D*, massive purple heterosite with some brown ferrisicklerite. See Fig. 2 for details of thin section.

triphylite. A photomicrograph showing the fabric of the alteration zones is reproduced in Fig. 2.

Neither tavorite nor barbosalite has been found as single crystals, although the latter occurs as very fine grained crystal aggregates in cavities. Tavorite not uncommonly occurs relatively free of impurity, but it also occurs admixed with barbosalite in such varying proportions that it presents a wide color range in specimens from yellow to yellow green, grass green, and dark green.

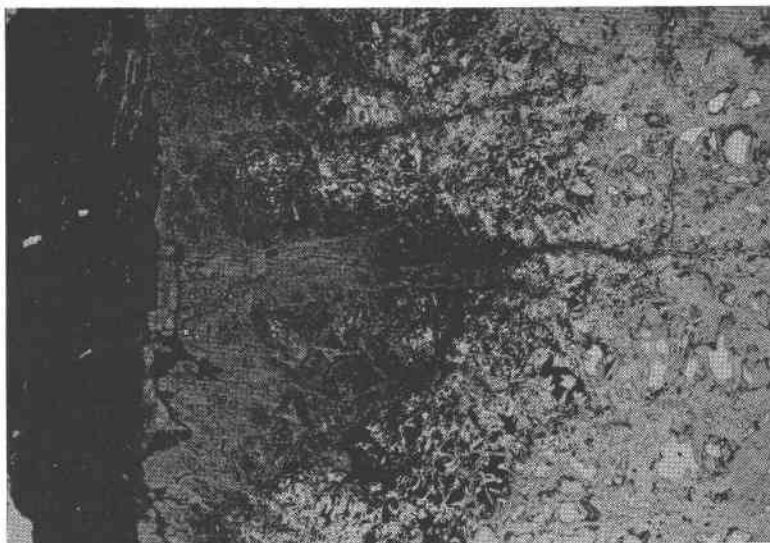


FIG. 2. Photomicrograph (plane polarized light, original dimensions 16×11 cm) showing details of alteration zoning. From left to right: heterosite (black), tavorite (dark gray), barbosalite (black), and porous, altered triphylite (white). The porous altered triphylite is lined with a network of bureaulite crystals, the shape of which is easily visible in contact with barbosalite.

TAVORITE

Tavorite (ta'-vor-ite) is a hydrous lithium ferric phosphate, the ferric analogue of montebasite, with iron substituting for aluminum. The ideal formula is $\text{LiFe}^{\text{III}}(\text{PO}_4)(\text{OH})$. The mineral is named for Dr. Elysiario Tavora, Professor of Mineralogy at the Universidade do Brasil, Rio de Janeiro.

Distribution

Tavorite occurs principally as discontinuous, greenish-yellow veinlets and disseminations, less than 5 mm. in width, at or near the contact of heterosite and barbosalite. It also occurs as a microscopic network (see Fig. 2) veining heterosite, ferrisicklerite, and barbosalite. Scattered flakes of tavorite are sparsely distributed along cleavage cracks in altered triphylite. Tavorite intimately replaces both barbosalite and crystals of bureaulite.

Physical properties

Tavorite is greenish yellow with a mean index of refraction as measured on aggregate mineral grains from vein material of 1.807. Flakes of tavorite scattered through triphylite have lower indices of refraction,

probably due to an excess of adsorbed water. The very fine grained habit prevented determination of the optical constants. The specific gravity is 3.288, as determined by means of an Adams-Johnston pycnometer of fused silica. The isomorphous and isostructural relationships of tavorite and montebasite, as indicated by comparison of their formulas and powder photographs, suggest that tavorite is triclinic.

Chemical composition

The sample of tavorite that was analyzed was determined by grain counts to contain less than 1 per cent of impurity, principally barbosalite but also hureaulite and heterosite. The sample was purified by hand picking of large grains, followed by crushing to free the intergrowths, which were removed by the Frantz isodynamic separator and by heavy liquids (methylene iodide). Clerici solution is unsuitable because of chemical attack.

The chemical analysis of tavorite is given in Table 1, column 2, where it may be compared with the calculated theoretical composition, column 1.

The mineral is essentially a hydrous lithium ferric phosphate. Its formula, as calculated from its chemical analysis (making one oxygen equivalent to 0.566) is: $(\text{Li}_{0.90}\text{Fe}''_{0.06}\text{Mn}''_{0.04})\text{Fe}'''_{0.94}(\text{PO}_4)_{0.99}(\text{OH})_{1.13}$. The ideal formula can be expressed as $\text{LiFe}'''(\text{PO}_4)(\text{OH})$, comparable to that of montebasite, $\text{LiAl}(\text{PO}_4)(\text{OH})$.

Tavorite yields water in a closed tube and gives a red (lithium) flame test. The mineral is easily soluble in hot dilute HCl and is slowly soluble in hot dilute HNO_3 and H_2SO_4 .

X-ray powder data

X-ray powder *d*-spacing data for tavorite are given in Table 3, column 2. The pattern is similar to but not identical with that of montebasite from the Sapucaia pegmatite (Table 3, column 1). The chief difference between the patterns is in cell size, but differences in intensities of corresponding lines also exist. The *d*-spacings for tavorite and montebasite are arranged by visual inspection so that reflections from provisionally equivalent planes are in the same line. Indexing the powder photograph may produce refinements.

BARBOSALITE

Barbosalite is a hydrous ferrous ferric phosphate, the ferric equivalent to scorzalite, with trivalent iron substituting for aluminum. Its ideal formula is $\text{Fe}''\text{Fe}'''_2(\text{PO}_4)_2(\text{OH}_2)$. It is isostructural with scorzalite and the synthesized compound prepared in the laboratory of J. W. Gruner

TABLE 1. CHEMICAL ANALYSIS AND RATIOS OF TAVORITE
Analyst: M. L. Lindberg

	Theoretical composition	Chemical analysis ¹	Ratios	Metal equivalent	Oxygen equivalent
LiO ₂	8.54	7.64	0.2557	0.5114	0.2557
FeO		2.39	0.0333	0.0333	0.0333
MnO		1.47	0.0207	0.0207	0.0207
Fe ₂ O ₃	45.70	42.57	0.2666	0.5331	0.7997
P ₂ O ₅	40.61	39.78	0.2802	0.5604	1.4011
H ₂ O+	5.15	5.76	0.3197	0.6394	0.3197
H ₂ O-		0.40			
Total	100.00	100.01			2.8302

Specific gravity 3.288.

Spectrographic analysis by J. D. Fletcher, U. S. Geological Survey, shows, in addition
0.0X Mg, Si, Na, Ca, Zn, Al
0.00X Cu
0.000X Cr, Be

Formula: $(Li_{0.90}Fe''_{0.06}Mn''_{0.04})Fe'''_{0.94}(PO_4)_{0.99}(OH)_{1.13}$

¹ Conventional methods were used to complete the analysis. Lithia was determined by a modified J. Lawrence Smith method. The alkali fusion was leached with water repeatedly until the washings gave no test for lithia with the hand spectroscope. The insoluble matter was then filtered off, ignited at a very low heat, powdered and mixed with additional NH₄Cl and CaCO₃, and a second fusion was made. This was again leached with water repeatedly until the washings gave no test for lithia. The insoluble matter was then dissolved in HCl and tested—before discarding—for lithia, which was absent. The (NH₄)₂CO₃—NH₄OH precipitation of CaCO₃ was dissolved and reprecipitated two additional times to free Li₂CO₃. The combined lithium salts were then evaporated to dryness and the ammonia salts driven off. Lithium was then converted to the sulfate and weighed; a correction was later made for a small amount of calcium precipitated as the oxalate. Spectrographic results (.0X%Na) eliminated the need for a separation of sodium and lithium.

and described as monoclinic ferrous ferric lazulite by Gheith (1953). The mineral is named for A. L. de M. Barbosa, Escola de Minas, Minas Gerais, Brazil.

Distribution

Barbosalite occurs principally as a very fine grained, dark blue-green layer between heterosite and porous triphylite. The contact with heterosite is well defined, but with the porous triphylite it is gradational, locally extending irregularly or along cleavage cracks into unaltered triphylite. The width of the layer ranges from a few millimeters to about 1 cm. In the cavities, barbosalite occurs as a massive material deposited among hureaulite crystals or as a thin coating of very fine crystalline

aggregates on hureaulite crystals. The cavities near the heterosite contain the most barbosalite. The contacts between hureaulite and barbosalite are sharp, suggesting little or no reaction and replacement.

Physical properties

The absorption of barbosalite is so strong that in thin section the mineral is opaque. In oil immersion, very fine grains show X and Y = dark blue green and Z = dark olive green. The absorption formula is X and Y > Z. The approximate indices of refraction are: $\alpha = 1.77$, $\gamma = 1.835$, and β is above but near 1.79. Optic angle could not be determined but is presumably large. The mineral is monoclinic. Its specific gravity as determined by an Adams-Johnston pycnometer is approximately 3.60, after correction for the contained tavorite.

Chemical composition

The sample of barbosalite that was analyzed contains, by grain count, one-fifth nonopaque material, with tavorite the only contaminant identifiable by optical or x-ray methods. The sample was purified by handpicking of large grains, followed by crushing to free admixed ma-

TABLE 2. CHEMICAL ANALYSIS AND RATIOS OF BARBOSALITE
Analyst: M. L. Lindberg

	Theoretical composition	Chemical analysis	Tavorite equivalent	Barbosalite equivalent	Barbosalite recalculated to 100 per cent	Ratios	Metal equivalent	Oxygen equivalent
LiO ₂		2.01	2.01					
FeO	18.35	10.26	0.63	9.63	13.10	0.1823	0.1823	0.1823
MnO		2.46	0.39	2.07	2.82	0.0398	0.0398	0.0398
Fe ₂ O ₃	40.79	41.81	11.20	30.61	41.65	0.2608	0.5216	0.7824
P ₂ O ₅	36.26	38.02	10.46	27.56	37.50	0.2642	0.5284	1.3210
H ₂ O	4.60	5.14	1.52	3.62	4.93	0.2736	0.5472	0.2736
H ₂ O—		0.20	0.11					
Total	100.00	99.90	26.32	73.49	100.00			2.5991
Specific gravity		3.511	3.288		3.598			

Spectrographic analysis by J. D. Fletcher, U. S. Geological Survey, shows, in addition:

0.0X Mg, Si, Na, Ca, Zn

0.00X Al

0.000X Cu

Formula: Fe''_{0.70}Mn''_{0.15}Fe'''_{2.01}(PO₄)_{2.03}(OH)_{2.10}

terials, which were removed by the Frantz isodynamic separator, and by differential settling in methylene iodide. Clerici solution was not used, because it was observed to react with the mineral. A microsample of pure barbosalite obtained from hureaulite-filled cavities gave a negative chemical test for lithium.

The chemical analysis of the impure barbosalite sample is given in Table 2, column 2. The lithia is attributed to admixed tavorite. The proportional amounts of constituents for tavorite (column 3) are subtracted from column 2 to give the barbosalite equivalent in column 4, which is recalculated to 100 per cent in column 5. The results compare favorably with the theoretical analysis (column 1). The formula, calculated from the analysis on a basis of ten oxygens equal to 2.60 is $\text{Fe}''_{0.70}\text{Mn}''_{0.15}\text{Fe}'''_{2.01}(\text{PO}_4)_{2.03}(\text{OH})_{2.10}$. The ideal formula can be expressed as $\text{Fe}''\text{Fe}'''_2(\text{PO}_4)_2(\text{OH})_2$ comparable to that of scorzalite $\text{Fe}''\text{Al}_2(\text{PO}_4)_2(\text{OH})_2$.

Barbosalite yields water in a closed tube. It is slowly soluble in hot dilute HCl and is insoluble in dilute HNO_3 and H_2SO_4 . It reacts slowly with alkali solutions and is attacked by Clerici solutions.

X-ray powder data

X-ray powder *d*-spacing data for a small sample of barbosalite free of impurity are given in Table 3, column 4; the corresponding powder pattern is shown in Fig. 3, film 4. The data for the analyzed sample of barbosalite, which contains admixed tavorite, are given in column 3; the corresponding pattern is film 3. Data and patterns for montebrasite, tavorite, and scorzalite are given in the same table and figure. For the pairs of isostructural minerals (1) montebrasite and tavorite and (2) scorzalite and barbosalite, data in Table 3 are arranged to present *d*-spacings from equivalent diffraction planes in the same line, and the offset in the powder patterns (see Fig. 3) illustrates differences in cell size. For the analyzed sample of barbosalite, which contains admixed tavorite, the *d*-spacings are arranged so as to indicate the contribution of barbosalite and tavorite to a given reflection, the mineral making the principal contribution in intensity is identified by a B or T.

The powder pattern of barbosalite corresponds, almost line for line, with that of scorzalite. The chief difference is in cell size, although small differences in intensities also are noted. The structural identity of barbosalite with a synthesized hydrous ferrous ferric phosphate (see Fig. 3, films 4 and 5) prepared in the laboratory of J. W. Gruner and described as monoclinic ferrous ferric lazulite by Gheith (1953) is evident. A dimorphous form of this compound was named lipscombite by Gheith (1953). Single crystal data by Katz and Lipscomb (1951) define lips-

TABLE 3. INTENSITY AND d -SPACING DATA FOR x -RAY POWDER PATTERNS OF MONTEBRASITE, TAVORITE, AND BARBOSALITE FROM THE SAPUCAIA MINE AND SCORZALITE FROM WHITE MOUNTAIN, CALIF. (Fe radiation and Mn filter)

1 Montebrasite		2 Tavorite		3 Barbosalite, with admixed tavorite ¹			4 Barbosalite, free of impurity		5 Scorzalite	
I	d	I	d	I		d	I	d	I	d
2	6.05 Å	1	6.37 Å	2	B	6.33 Å	2	6.33 Å	3	6.19 Å
$\frac{1}{2}$	5.90									
2	5.15	5	4.99	1	T	4.97				
1	4.84	1	4.76	6	B	4.84	6	4.84	4	4.73
9	4.68	3	4.68	1	T	4.68				
2	3.755	2	3.95							
4	3.351	1	3.439							
4	3.285	1	3.400							
				10	B	3.361	10	3.361	10	3.248
6	3.221	2	3.323	10	B	3.320	8	3.313	9	3.204
6	3.169	9	3.285							
		$\frac{1}{2}$	3.244	4	B	3.239	6	3.239	5	3.152
				4	B	3.160	6	3.160	3	3.077
10	2.971	10	3.045	4	T	3.045				
2	2.578	1	2.655	$\frac{1}{2}$	BT	2.655	1	2.652		
				2	B	2.614	3	2.614	4	2.556
2	2.502	1	2.558	$\frac{1}{2}$	T	2.558				
$\frac{1}{2}$	2.474	1	2.542	$\frac{1}{2}$	T	2.536				
5	2.405	4	2.474	1	T	2.474				
1	2.358	1	2.441	$\frac{1}{2}$	BT	2.439	1	2.439		
				$\frac{1}{2}$	B	2.410	1	2.407	1	2.347
3	2.296	2	2.360							
				3	B	2.327	4	2.327	3	2.264
$\frac{1}{2}$	2.277									
2	2.210	1	2.287	2	B	2.292	3	2.292	2	2.226
4	2.137	2	2.206	$\frac{1}{2}$	T	2.208				
1	2.108									
$\frac{1}{2}$	2.058	1	2.156	$\frac{1}{2}$	T	2.152				
$\frac{1}{2}$	2.033	1	2.113	$\frac{1}{2}$	BT	2.113	1	2.108	1	2.055
				1	B ²	{2.080}	2	{2.080}	2	2.012
				1	B	{2.057}		{2.057}	$\frac{1}{2}$	1.989
3	1.969	1	2.028	2	B	2.027	3	2.027	1	1.976
$\frac{1}{2}$	1.943	1	1.998	$\frac{1}{2}$	T	1.998				
$\frac{1}{2}$	1.931	1	1.973	$\frac{1}{2}$	T	1.973				
3	1.900	2	1.938	$\frac{1}{2}$	T	1.938			$\frac{1}{2}$	1.828
				2	B	1.880	2	1.877	1	1.811
$\frac{1}{2}$	1.823									
2	1.795	$\frac{1}{2}$	1.851	$\frac{1}{2}$	T	1.854				
2	1.758	1	1.823	1	B	1.828	1	1.828	1	1.789

¹ B, for barbosalite, and T, for tavorite, indicate the mineral making the principal contribution to the intensity of a given d -spacing.

² { }, bracket indicates a band between 2.080 and 2.057 Å.

TABLE 3—(continued)

1 Montebrasite		2 Tavorite		3 Barbosalite, with admixed tavorite ¹			4 Barbosalite, free of impurity		5 Scorzalite	
<i>I</i>	<i>d</i>	<i>I</i>	<i>d</i>	<i>I</i>		<i>d</i>	<i>I</i>	<i>d</i>	<i>I</i>	<i>d</i>
				$\frac{1}{2}$	B	1.788	1	1.797	$\frac{1}{2}$	1.741
$\frac{1}{2}$	1.683	$\frac{1}{2}$	1.751	$\frac{1}{2}$	B	1.757	$\frac{1}{2}$	1.776		
				1	T	1.721	1	1.757	$\frac{1}{2}$	1.688
1	1.673	2	1.722	$\frac{1}{2}$	BT	1.706	$\frac{1}{2}$	1.746	$\frac{1}{2}$	1.667
1	1.656	1	1.705	2	B	1.681	$\frac{1}{2}$	1.726		
$\frac{1}{2}$	1.646			3	BT	1.658	3	1.681	3	1.625
2	1.623	3b	1.662	$\frac{1}{2}$	T	1.642	3	1.658	2	1.605
5	1.610	2	1.642	2	BT	1.623	3	1.625	2	1.578
1b	1.586	2	1.620	2	B	1.610	3	1.610	$\frac{1}{2}$	1.563
				1	B	1.584	2	1.584	3	1.541
1	1.538	$\frac{1}{2}$	1.560							
1	1.527	$\frac{1}{2}$	1.552	$\frac{1}{2}$	BT	1.553	$\frac{1}{2}$	1.550		
1	1.487	1b	1.520	$\frac{1}{2}$	T	1.520				
1	1.477									
$\frac{1}{2}$	1.465	$\frac{1}{2}$	1.501				$\frac{1}{2}$	1.476	1	1.443
2b	1.448									
				1	B	1.466	1	1.465	2	1.416
2	1.427	1	1.453	$\frac{1}{2}$	BT	1.459	1	1.458	$\frac{1}{2}$	1.411
2	1.409	2	1.437	1	BT	1.438	1	1.439	1	1.393
1	1.392	$\frac{1}{2}$	1.424							
$\frac{1}{2}$	1.369									
$\frac{1}{2}$	1.352	$\frac{1}{2}$	1.403	1	BT	1.401	$\frac{1}{2}$	1.399	$\frac{1}{2}$	1.368
$\frac{1}{2}$	1.342	$\frac{1}{2}$	1.397	$\frac{1}{2}$	B	1.389	1	1.389	1	1.356
				$\frac{1}{2}$	B	1.372	1	1.374	1	1.340
$\frac{1}{2}$	1.322	$\frac{1}{2}$	1.360	$\frac{1}{2}$	B	1.355	1	1.353	1	1.326
$\frac{1}{2}$	1.314	$\frac{1}{2}$	1.339							
4	1.291	2	1.327	$\frac{1}{2}$	T	1.328				
				1	B	1.317	$\frac{1}{2}$	1.318		
1	1.274	1	1.300	3	B	1.309	4	1.309	4	1.280
1	1.265	1	1.285	$\frac{1}{2}$	B	1.282	$\frac{1}{2}$	1.281	$\frac{1}{2}$	1.263
2	1.253	2	1.271	$\frac{1}{2}$	BT	1.271	$\frac{1}{2}$	1.271	$\frac{1}{2}$	1.246
$\frac{1}{2}$	1.215	$\frac{1}{2}$	1.238	$\frac{1}{2}$	BT	1.239	$\frac{1}{2}$	1.238		
$\frac{1}{2}$	1.205									
				$\frac{1}{2}$	B	1.229	1	1.229	$\frac{1}{2}$ b	1.998
				1	B	1.218	1	1.218		
2	1.179	$\frac{1}{2}$	1.220							
1	1.171	$\frac{1}{2}$ b	1.210							
$\frac{1}{2}$	1.163	$\frac{1}{2}$	1.197							
2	1.153	1	1.181	1	B	1.171	2	1.171	1	1.129
				1	B	1.160	2	1.160	1	1.118
				1	B	1.128	1	1.127		
$\frac{1}{2}$	1.137	$\frac{1}{2}$	1.164				1	1.107		

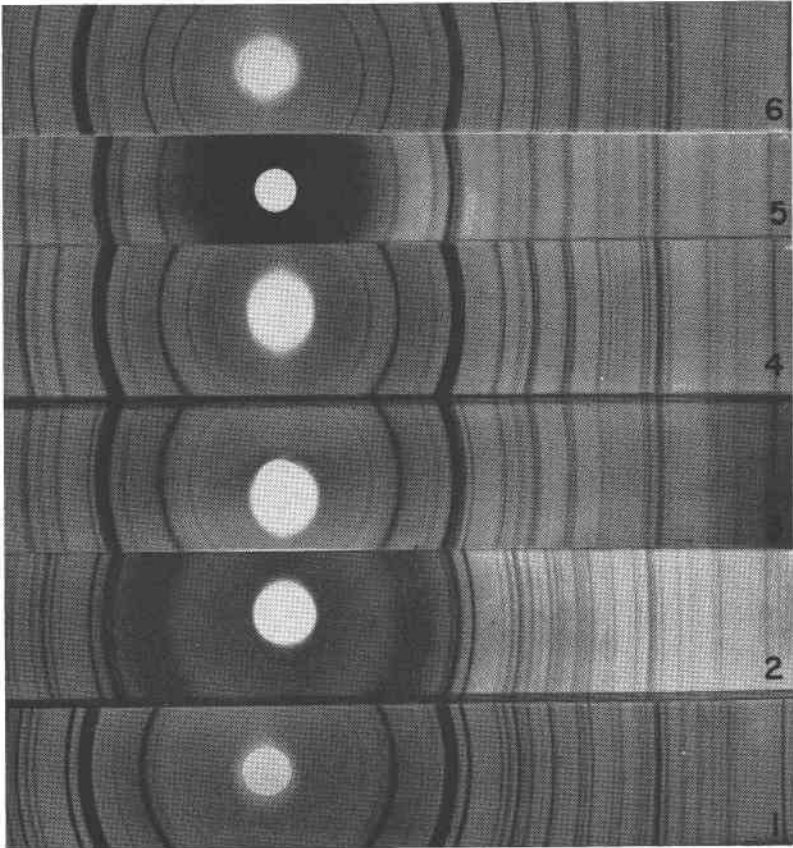


FIG. 3. Comparison of x -ray powder photographs: (1) montebrasite (Sapucaia pegmatite); (2) tavorite (analyzed sample, Sapucaia pegmatite); (3) barbosalite (analyzed impure sample containing tavorite, sapucaia pegmatite); (4) barbosalite (pure microsample from hureaulite-bearing cavities, Sapucaia pegmatite); (5) synthesized ferrous ferric lazulite; and (6) scorzalite (White Mountain, Calif.). The patterns are aligned on the right to show differences in cell size between tavorite and montebrasite and between barbosalite and scorzalite.

combite as tetragonal in symmetry. Gheith (1953, p. 612) demonstrates that the x -ray powder patterns of both compounds are similar, but that they differ from lazulite in having d -spacings corresponding to a larger unit cell.

From this correlation it is concluded that barbosalite is monoclinic as are lazulite and scorzalite (Pecora and Fahey, 1950). The unit cell size of barbosalite is essentially that of the synthesized ferrous ferric lazulite but larger than that of scorzalite. Minor discrepancies between the x -ray data for barbosalite (this paper) and for ferrous ferric lazulite

(Gheith, 1953, p. 617) are probably explained by the fact that Gheith's patterns show the effect of unfiltered iron radiation with a consequent (1) broadening of reflection and loss of resolution, and (2) occurrence of separate reflections, representing alpha and beta radiation, of planes with the same *d*-spacing.

ORIGIN

The complex set of chemical reactions leading to the formation of the secondary phosphate mineral suite involve (1) hydration, (2) partial or complete oxidation of the ferrous and manganous ions, and (3) solution and reprecipitation of several ions to form new compounds. How much of this chemical action was the result of hydrothermal solutions and how

TABLE 4. CHEMICAL FEATURES OF TAVORITE, BARBOSALITE, AND OTHER PHOSPHATE MINERALS FROM THE SAPUCAIA PEGMATITE

Mineral	Hydration	Oxidation state		Presence of lithium
		Iron	Manganese	
Triphylite	anhydrous	ferrous	manganous	yes
Heterosite	nonessential water	ferric	manganic	no
Ferrisicklerite	nonessential water	ferric	manganous	yes
Hureaulite	acid water and water of crystallization	ferrous	manganous	no
Vivianite	water of crystallization	ferrous	manganous	no
Tavorite	hydroxyl water	ferric	manganous	yes
Barbosalite	hydroxyl water	ferrous ferric	manganous	no
Frondelite	hydroxyl water	ferric	manganous manganic	no

much the result of ground water in a humid tropical region has not as yet been established with certainty. Most of the hand specimens in our collection were obtained from within 20 meters of the surface and presumably within the range of ground-water alteration. It is our present belief, however, that much of the direct alteration of triphylite was caused by hydrothermal attack late in the consolidation history of the pegmatite.

Chemical features of tavorite, barbosalite, and associated phosphate minerals are arranged for comparison in Table 4. Triphylite is thus the only anhydrous mineral² listed, and presumably it is the original source

² In heterosite and ferrisicklerite, water is present in small and variable amounts, and is considered by Mason (1941, p. 148) to be "not constitutional, but held by forces of adsorption."

of most of the constituents, other than water, necessary to form the secondary phosphate minerals. Iron and manganese in hureaulite and vivianite are not oxidized. With respect to triphylite, hureaulite is enriched in manganese and vivianite is enriched in iron. Heterosite, on the other hand, represents a complete oxidation of iron and manganese, and ferrisicklerite a partial oxidation, with respect to triphylite. In tavorite and barbosolite the small amount of manganese present is not in the oxidized state, although the iron is substantially in the ferric state. Barbosolite and frondelite contain approximately the same amount of iron plus manganese, but frondelite is deficient in phosphate and high in hydroxyl with reference to barbosolite.

Of the minerals listed in Table 4, the relations of which are illustrated in Figs. 1 and 2, tavorite is certainly the youngest to have formed and barbosolite the next to youngest. Late in the alteration history, therefore, lithium was available and utilized to form tavorite by solutions attacking many of the earlier formed minerals. Whether this lithium was obtained by direct alteration of triphylite or its intermediate product ferrisicklerite cannot be established. The concentration of tavorite and barbosolite near the heterosite-ferrisicklerite alteration zone would strongly favor their formation through continued alteration of the intermediate products rather than from triphylite itself.

Fractures coinciding with cleavage directions of triphylite and heterosite have played an important role in guiding the development of the alteration products. This favorable physical relation applies to both the hydrothermal and weathering stages of alteration.

Chemical and mineralogical investigations of our suite of specimens are still in progress, and further information on the paragenesis of the secondary phosphate minerals will no doubt be revealed. Current studies of similar phosphate minerals from other granite pegmatites in this and other countries will contribute much to our understanding of the complex alterations involved. Much of the material is, however, so admixed and so difficult to identify and purify, that progress is unfortunately a slow affair.

PROBLEM OF NOMENCLATURE

The discovery of tavorite and barbosolite extends our knowledge of the natural substitution of ferric ions for aluminum in two different mineral structures. New mineral names are justified in both.

In the lazulite mineral group, three or four ideal end members can now be accepted as naturally occurring compounds. The substitution of ferrous ions for magnesium in lazulite results in the formation of scorzalite (Pecora and Fahey, 1950), and the additional substitution of ferric

ions for aluminum results in barbosalite. The fourth member of the group, as yet undiscovered, would be a hydrous magnesium ferric phosphate. A hydrous manganous ferric phosphate, also not yet discovered, may be predicted. Intermediate compositions within the mineral group can be conveniently designated by use of adjectival modifiers (Schaller, 1930). The synthesized monoclinic ferrous ferric lazulite described by Gheith (1953) would be analogous to barbosalite.

Tavorite represents the ferric analogue of montebasite, and both are here accepted as the ideal end members with hydroxyl ions present instead of fluorine. Excess of fluorine over hydroxyl, as in amblygonite, denotes further chemical variation in the mineral group. Tavorite, montebasite, and amblygonite are, then, three different members of the amblygonite mineral group. Adjectival modifiers can denote intermediate compositions.

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