THE PARAGENESIS OF THE CENTER STRAFFORD, NEW HAMPSHIRE, PEGMATITE

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Introduction

About two miles northwest of Center Strafford, in southeastern New Hampshire, a pegmatite is quarried for feldspar and mica. It is especially interesting for its abundance of unusual phosphates; in particular triphylite, graftonite, fairfieldite, and a number of their alteration products. Also noteworthy is the relative abundance of loellingite. These complex constituents make up only about 10 per cent of the pegmatite, microcline, muscovite, and quartz constituting the remainder.

The Pegmatite

The granitic body of which the Center Strafford pegmatite is a portion, is post-Carboniferous in age, being part of a group of granites and granite-gneiss considered by F. J. Katz (1917) to be equivalent to the Biddeford granite of southwestern Maine. In the vicinity of Center Strafford the granite has intruded schists and phyllites of Carboniferous (Pennsylvanian?) age.

The pegmatite is roughly lenticular in shape, the lens-shaped mass standing almost on edge, and is located on the side of a steep slope. The widest part is about 40 feet in width. The floor of the quarry is flat and cuts into the hill 150 feet, where it rapidly wedges out. The walls of the present quarry at its head are about 50 feet high. According to the present operator, Mr. Buzzo, of Center Strafford, a water-filled pit at the head of the quarry goes down an additional 60 or 70 feet, and presumably reached the bottom of the lens.

The pegmatite is enclosed in a wall rock of distinctly gneissic granite almost lacking in ferromagnesium minerals. Within a few feet of the pegmatite border the granite contains a small amount of black tourmaline, and at the border there is a noticeable concentration of tourmaline several inches wide.

The wall rock is uniformly fine grained and makes a sharp boundary with the pegmatite. Along the northeast border of the pegmatite is a band of typical graphic granite from several inches to a foot or more in width. The graphic granite is in sharp contact with the gneissic wall rock on one side and the typical coarse grained pegmatite on the other and is entirely confined to this peripheral zone. Coarse microcline crystals with large masses of anhedral quartz make up most of the body of the pegmatite, but none of this microcline shows a graphic quartz intergrowth.

The minerals introduced into the pegmatite during the pneumatolytic and hydrothermal stages are limited in position entirely to the southeast pegmatite-wall rock contact, indicating that there was a through-going channel along the contact to which the mineralizing vapors and solutions had access.

PARAGENESIS

There were three distinct stages of mineralization at Center Strafford. The first, or primary stage, represents the crystallization of a rest-magma not greatly different in composition from a normal granitic magma. The peripheral zones of graphic granite and tourmaline, and the coarsely crystalline microcline, muscovite, and quartz of the main pegmatite body crystallized at this time.

The second stage of mineralization has been termed pneumatolytic, since it apparently represents a high temperature stage of mineralization by magmatic emanations rich in volatile constituents. Large quantities of beryl, triphylite, apatite, and albite were introduced at this time, almost entirely by a replacement process.

TABLE 1. SEQUENCE OF MINERALIZATION

Magmatic	Microcline	$KAlSi_3O_8$
	Muscovite	$KAl_2(Si, Al)_4O_{10}(OH)_2$
	Tourmaline	$Na(Fe,Mg)_3B_3Al_3(Al_3Si_6O_{27})(OH)_4$
	Quartz	SiO_2
Pneumatoylitic	Beryl	$Al_2Be_3Si_6O_{18}$
	Triphylite	$Li(Fe,Mn)PO_4$
	Graftonite	$(Fe,Mn,Ca)_3PO_4$
	Manganapatite	$(CaF)Ca_4(PO_4)_3$ with Mn
	Albite	$NaAlSi_3O_8$
Hydrothermal	Amblygonite	$LiAl(F,OH)PO_4$
	Rhodochrosite	$MnCO_3$
	Fairfieldite	$Ca_2Mn(PO_4)_2 \cdot 2H_2O$
	Microcline	$KAlSi_3O_3$
	Quartz	SiO_2
	Columbite	$(Fe,Mn)(Nb,Ta)_2O_6$
	Muscovite	$KAl_2(Si,Al)_4O_{10}(OH)_2$
	Garnet	$(Fe,Mn)_3Al_2(SiO_4)_3$
	Loellingite	$FeAs_2$
	Cassiterite	SnO_2
Low temperature hydrothermal	Autunite	$Ca(UO_2)_2(PO_4)_2 \cdot 8H_2O$
	Vivianite	$Fe_3(PO_4)_2 \cdot 8H_2O$
	Eosphorite	$AlPO_4 \cdot (Mn,Fe)(OH)_2 \cdot H_2O$
	Heterosite	$(Fe,Mn)PO_4 \cdot H_2O$
	Ferri-sicklerite (?)	$Li(Mn,''Fe''''')PO_4$

The third, or hydrothermal stage of mineralization, resulted in the progressive introduction of a large number of minerals by hydrothermal solutions. The most abundant of these are rhodochrosite, quartz, muscovite, garnet, and loellingite. The hydrothermal stage is considered to have been an essentially continuous period of replacement, during which the temperature of the solutions gradually fell. The final action of the solutions, as their temperature approached that of meteoric waters near the surface was an alteration of previously formed minerals. The most abundantly altered mineral was triphylite, which changed to several hydrous iron and manganese phosphates.

DESCRIPTION OF THE MINERALS

Microcline. Microcline-perthite is the most abundant mineral in the pegmatite, where it occurs in rough subhedral crystals up to two feet across. On the border of the pegmatite it is intergrown with quartz as graphic granite. The perthite lamellae are about one half to one mm. wide, and spaced two to three mm. apart.

A small amount of hydrothermal microcline has formed in narrow veins with albite and amblygonite, cutting triphylite.

Muscovite. Muscovite of two generations is clearly represented. The primary muscovite was one of the earliest formed minerals. It occurs as subhedral crystals up to one foot across, and several inches thick entirely enclosed in microcline. However, there is no evidence for replacement, but rather, a complete overlap of the period of crystallization of feldspar over that of muscovite.

A pipe-like mass of muscovite approximately 10 feet in diameter and 20 feet high, near the head of the quarry, has clearly replaced a mass of microcline and quartz. The muscovite crystals in this case are smaller, and the interstices between them are occupied by remnants of the replaced microcline and quartz.

Tourmaline. All the tourmaline seen was the black iron-rich variety, which occurs in prismatic crystals up to 4 cm. in length and 2 cm. in diameter. Its occurrence is almost entirely confined to the border of the pegmatite. Within the main body of the pegmatite it is found as small flattened crystals within large crystals of muscovite. They are most commonly flattened parallel to a prism face. Figure 1 illustrates a tourmaline crystal of this type flattened parallel to $a\{11\bar{2}0\}$. The other forms present are $m\{10\bar{1}0\}$, and $r\{10\bar{1}1\}$. There seems to be no definite oriented intergrowth of the tourmaline and muscovite, other than that the direction of flattening of the tourmaline crystals is always parallel to the basal cleavage of the muscovite.

Quartz. Quartz was the last magmatic mineral to crystallize. It forms large anhedral masses interstitial to the microcline. It is colorless, or slightly smoky, and has been badly shattered and stained by iron and manganese oxides.

Quartz of a later generation is indicated by narrow veins cutting triphylite and albite, and therefore post-albite.

Beryl. Pale green to white beryl occurs in considerable abundance as rather large crystals. The largest crystal exposed on the quarry wall was about one foot in diameter and two feet long. Crystals from two to six inches in diameter were quite abundant on the west wall of the quarry. The crystals generally occur imbedded in badly fractured masses of quartz, and have often been partially replaced by apatite and albite.

Triphylite. A nodular mass of triphylite of unusual size was developed at Center Strafford. The mass was approximately 10 feet across. The triphylite is medium brown in color, showing large fresh cleavage surfaces but rarely any crystal outline. One rough prism section was found, about 3 cm. across, almost entirely altered to a hydrous manganese oxide.

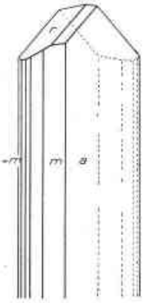


FIG. 1. Flattened Crystal of Tourmaline

Table 2 gives the results of an analysis of this triphylite.

The Center Strafford triphylite is orthorhombic, exhibits one perfect cleavage, {001}, and a less perfect cleavage at right angles to the first, {010}. The fracture is conchoidal. It contains abundant minute inclusions oriented parallel to the cleavages, of unknown nature. It has the following optical properties, which are in very close agreement with those given by Larsen and Berman (1934) for a triphylite with 26.85 per cent FeO.

	n		
X=c	1.686	±0.002	Biaxial (+), 2V=20°
Y=a	1.687		
Z=b	1.693		Dispersion very strong, $r>v$.

Graftonite. The rare mineral graftonite occurs in small reddish brown

TABLE 2. ANALYSIS AND MOLECULAR RATIOS OF TRIPHYLITE

	1.	2.	3.		4.
FeO	29.13	29.05	0.4044	$0.6448 = 2 \times 0.323$	29.38
MnO	15.96	15.92	0.2245		16.06
MgO	0.42	0.42	0.0104		
CaO	0.31	0.31	0.0055		
Li_2O	8.86	8.84	0.2957	$0.2988 = 1 \times 0.299$	9.46
Na_2O	0.15	0.15	0.0024		
K_2O	0.07	0.07	0.0007		
P_2O_5	44.87	44.76	0.3116	$0.3116 = 1 \times 0.312$	45.10
H_2O	0.48	0.48	0.0300		
Insol.	0.21				
	100.46	100.00			100.00

1. Center Strafford triphylite, F. A. Gonyer, analyst.
2. Analysis calculated to 100%, after deducting insolubles.
3 Molecular ratios.
4. Calculated composition for $Li(Fe, Mn)PO_4$, with Fe:Mn = 1.72:1.

intergrowths with triphylite. This mineral has previously been described from Grafton, New Hampshire, by S. L. Penfield (1900), from North Groton, New Hampshire by H. Berman (1927), and most recently from Greenwood, Maine, by J. J. Glass and J. J. Fahey (1937). In the first two localities it occured interlaminated with triphylite, probably as a simultaneous crystallization. This same relationship seems to hold at Center Strafford, although the evidence is not clear. The optical properties of the Center Strafford graftonite correspond closely to those given by Berman for graftonite from North Groton, and are as follows:

	n		
X	1.700	±0.002	Biaxial (+), 2V = 50°
Y	1.706		
Z	1.726		Dispersion strong, $r > v$.

Manganapatite. This mineral occurs commonly in the pegmatite in dark green, transparent, anhedral masses, or less commonly as opaque brown crystals. Both color varieties contain manganese, and are uniaxial (−), with $\omega = 1.632$ (±0.002).

Albite. The platy form of albite commonly termed cleavlandite is an abundant mineral of the pegmatite, having replaced large quantities of microcline, and some quartz, beryl, triphylite, and apatite.

Amblygonite. Amblygonite was found only in small amounts associated with albite and microcline in narrow veins cutting triphylite. It is visible only in thin section, where it is easily recognizable because of polysynthetic twinning together with high birefringence.

Rhodochrosite. Pale pink, fine grained rhodochrosite occurs in veins cutting triphylite. In several instances it has been partially replaced by loellingite. It is uniaxial (−), with $\omega = 1.832$ (± 0.003).

Fairfieldite. Fairfieldite, identified optically, occurs as pale salmon pink, fine grained masses with rhodochrosite and triphylite.

Columbite. Columbite, identified by its appearance under the microscope and its specific gravity (D = 5.46), occurs widely scattered throughout the pegmatite in small poorly developed, tabular crystals, commonly associated with the second generation quartz, but it can be definitely dated only as post-albite.

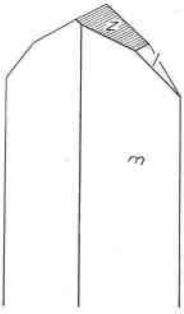


FIG. 2. Crystal of Loellingite

Garnet. Garnet was found in a single mass several feet in diameter, and nowhere else in the pegmatite. Part of the garnet has replaced some of the second generation muscovite, and both were later partially replaced by loellingite. A refractive index of 1.790 and a specific gravity of 4.14 indicate the garnet to be almandite-spessartite. It is red in color, and completely isotropic. It occurs as individual crystals up to 2 inches in diameter, the dodecahedron being the most common form. Occasionally the trapezohedron *n*{211} has developed.

Loellingite. The sulphide-rich stage at Center Strafford was characterized by an abundance of loellingite. It is tin white in color, sometimes tarnished brown. It occurs in rough prismatic crystals up to 5 cm. in length, and in irregular crystalline masses. Rarely small crystals, up to 2 mm. in length, have developed in considerable perfection. Such a crystal is illustrated in Fig. 2. The forms present are: *m*{110}, *l*{011}, and *z*{012}. The base *c*{001} is sometimes present.

The presence of loellingite in the pegmatite is almost entirely confined to the concentrations of triphylite, muscovite, and garnet previously described, and it has replaced all three of these minerals.

Table 3 gives the results of an analysis of this loellingite.

TABLE 3. ANALYSIS AND MOLECULAR RATIOS OF LOELLINGITE

	1.	2.	3.	4.
Fe	27.89	27.95	$0.5011=1\times0.5011$	27.18
As	70.94	71.09	$\left.\begin{matrix}1.054\\0.030\end{matrix}\right\}=2\times0.542$	72.82
S	0.96	0.96		
	99.79	100.00		100.00

1. Loellingite from Center Strafford, F. A. Gonyer, analyst.
2. Composition calculated to 100%.
3. Molecular ratios.
4. Calculated composition for FeAs$_2$.

Cassiterite. Cassiterite in rough crystals up to one cm. across occurs in small amounts in triphylite and quartz, and replacing loellingite. The pleochroism is distinct, ω = colorless, ϵ = dark reddish brown. Pleochroism is a property not commonly given for cassiterite, and is generally noted only in pegmatitic material.

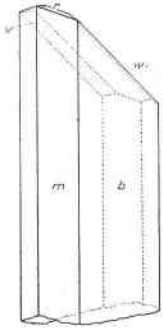


FIG. 3. Crystal of Vivianite

Autunite. Autunite occurs as small pale green flakes on quartz, feldspar, or muscovite. It fluoresces a strong yellowish green under an ultraviolet light source.

Vivianite. Vivianite is one of the most common triphylite alteration products. It occurs as thin films along cleavage planes of the triphylite, or as small masses of powdery material, and rarely as small rough crystals. A typical crystal is shown in Fig. 3. It is monoclinic, with the forms $b\{010\}$, $m\{110\}$, $v\{\bar{1}11\}$, $w\{\bar{1}01\}$, and $r\{\bar{1}12\}$. The mineral is deep blue in color, and strongly pleochroic from deep blue to colorless, conforming with known optical properties for this mineral.

Eosphorite. Eosphorite occurs as small, pale brown, poorly formed crystals on triphylite or its alteration products. Its optical properties correspond closely to those of eosphorite from Branchville, Connecticut (Larsen and Berman, 1934). Eosphorite from Center Stafford has the following optics:

	n		
X	1.640	±0.002	Biaxial (−), 2V=35°
Y	1.662		
Z	1.666		Dispersion perc., $r>v$.

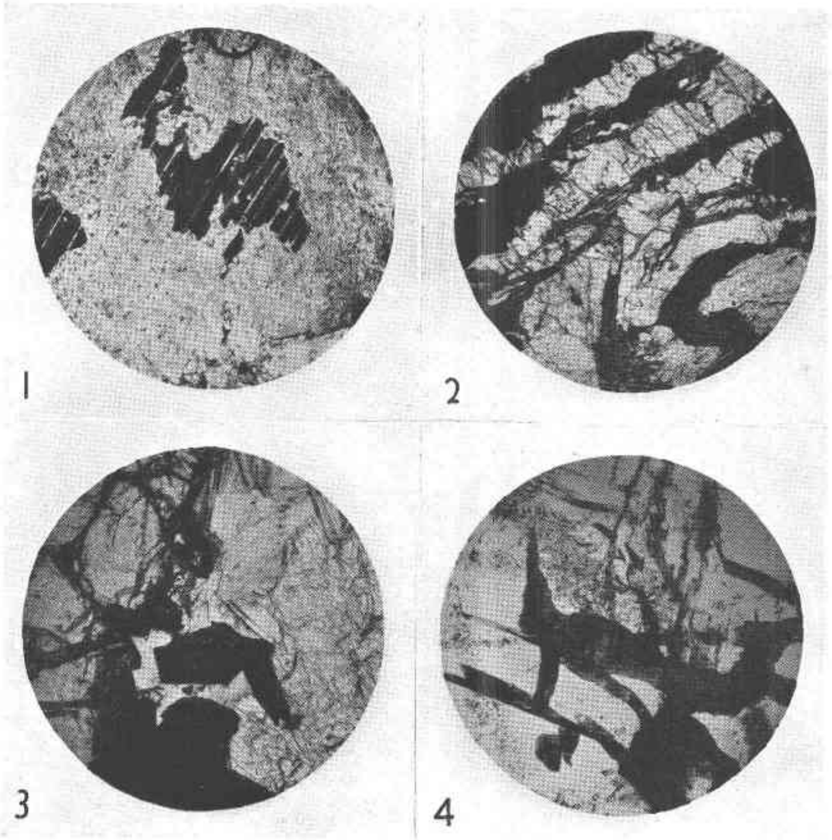
Heterosite. Heterosite occurs as an alteration product of triphylite. It is nearly black in the mass, with a dark red powder. It is optically negative, with a moderate optic angle, has a mean refractive index of about 1.84, and a high birefringence. It is strongly pleochroic from greenish grey to deep red.

Other alteration products. Quensel (1937) has described an alteration product of triphylite from the lithium pegmatite of Varutrask, Sweden, which resembles sicklerite, but has a much higher content of iron, and higher indices of refraction. He called this mineral ferri-sicklerite to distinguish it from sicklerite as described by W. T. Schaller (1912). One of the triphylite alterations from Center Strafford resembles Quensel's ferri-sicklerite, and it may be that the two are the same. In a direct comparison of the material in question from Center Strafford, and ferri-sicklerite from Varutrask kindly furnished by Dr. Quensel, the two minerals resemble each other rather closely both physically and optically. The Center Strafford material is dark brown or black in color, and has a dark brown powder. It is biaxial, with a moderate optic angle, has a mean refractive index of approximately 1.80, and is strongly pleochroic from light to dark brown. Due to high absorption, optical data are obtained with great difficulty, so the exact optical correspondence of the two is not certain.

A specimen from Center Strafford, collected by Mr. Gunnar Bjareby, of Boston, Massachusetts, contained a mineral as yet unindentified. It occurs as small botryoidal masses of radiating fibres, clearly an alteration of triphylite. It most closely resembles dufrenite, but its indices of refraction are much lower, and its pleochroism more intense. Qualitatively it was found to be essentially a hydrous phosphate of iron and manganese. The following optical properties were determined:

	n		
X	1.787	±0.003	Biaxial (+), 2V=85°
Y parallel to elong. fibres	1.813		Pleochroism: X=bright green Y=reddish brown

The three minerals just described, heterosite and the two uncertain alteration products, are apparently members of an alteration series from pure or slightly altered triphylite to the final end products of alteration,



(1) Amblygonite, showing polysynthetic twinning. Crossed nicols. 28×
(2) Muscovite (dark grey) and loellingite (black) replacing triphylite (light grey). Crossed nicols. 20×.
(3) Loellingite (black) replacing muscovite (light grey) and garnet (dark grey). Ordinary light. 20×.
(4) Triphylite (light) altering to ferri-sicklerite(?) (dark). Ordinary light. 20×.

hydrous manganese and iron oxides. Samples examined from various parts of a small mass will vary greatly in their indices of refraction, and other optical and physical properties. It was found, therefore, impractical to deal with this material in a detailed manner.

SUMMARY

The Center Strafford pegmatite is a lens shaped body enclosed in a gneissic wall rock, which it has intruded. The main body of the pegmatite, composed of microcline and quartz, has formed by crystallization of a rest-magma. The complex constituents have been introduced by an extensive replacement process. Beryl, triphylite, graftonite, manganapatite, and albite were the first of these, and have been classified as pneumatolytic, since they appear to have been introduced by vapors or solutions high in volatile constituents. Following these and apparently deposited by true hydrothermal solutions, were a number of minerals, the most abundant of which were rhodochrosite, muscovite, garnet, and loellingite. As the temperature of the solutions approached those of near surface meteoric waters, the earlier formed phosphates were extensively altered to vivianite, eosphorite, heterosite, and others.

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