PARAGENESIS OF THE MINERALS FROM BLUEBERRY MOUNTAIN, WOBURN, MASSACHUSETTS

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Introduction

Blueberry Mountain (300 feet) lies 9 miles N.N.W. of Boston, 3½ miles north of the limits of the Boston Basin, in the southeast part of Woburn near the Winchester boundary line. It is one of numerous hills of about the same height which form the main relief of the Boston quadrangle.

In 1913 a small quarry was opened about 400 feet northeast of the present operations by the Winchester Rock and Brick Company. The life of this development was short, ending in 1919 when the project was taken over by the General Sand and Gravel Company of Easton, Pennsylvania. Due to more efficient management and greater financial resources, this company extended its operations to the site of the present quarry. The abandonment of the old quarry was caused by trouble with rock breaking along the joint system. The dip and strike of the joint system is such that in blasting, great overhanging ledges resulted under which it was dangerous for the men to work. When worked from the southern side of the hill this difficulty was overcome.[1] Up to the present time over 4,000,000 tons of rock and 500,000 tons of overburden have been removed, and as yet only a small part of the hill has been quarried.

Geologic History

The principal rock of the quarry is the pre-Carboniferous granodiorite which is younger than the Waltham gneiss over which it is thrust, younger than the gabbrodiorite into which it is intruded, and probably older than the granite which lies a little to the north. Into all these rocks aplite and pegmatite dikes have been intruded.

The igneous rocks may have been derived from a magma which intruded the pre-Cambrian Waltham gneiss, incorporated some of the wall-rock and differentiated in place, producing in turn the Salem granodiorite, the Wakefield granite, and dikes of aplite and pegmatite. Later intrusive activity resulted in dikes in the granodiorite and lit-par-lit injections in the gneiss. Still later hydrothermal activity produced a complicated series of minerals.

After the formation of the pegmatites and the subsequent hydrothermal activity, thrust faulting forced the Salem granodiorite over the

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[1] Miller, Robert B., Pegmatites of Blueberry Mountain, Winchester Highlands, Massachusetts (unpublished).

Waltham gneiss, which is exposed on the east side of the quarry. The main thrust faults are associated with smaller thrusts and normal faults. The sub-parallel arrangement and lens-shape of the pegmatites indicate that these bodies were injected along planes of weakness. Their sharp contacts with the granodiorite and gneiss show that they were not formed in place. During or after these movements a complicated system of small veins traversed the pegmatites, granodiorite and gneiss indiscriminately. These veins may have been produced by torsional stresses; renewed hydrothermal activity caused them to be mineralized.

Paragenesis

The mineralogical sequence is divided into three main stages—magmatic, pegmatitic, and hydrothermal. The hydrothermal phase is subdivided into three stages of falling temperatures and a zeolite phase.

The writer wishes to introduce at this time a new term, which he believes will fill a need long felt. There are certain minerals that form under conditions nearly similar to those which produce the zeolites; for these minerals the writer proposes the term "anchi-zeolite," meaning "near zeolite." Under this term will be included such minerals as prehnite, datolite, babingtonite, and other minerals formed under similar conditions.

The minerals of the several phases occur in three different types of deposits. The magmatic minerals are found in the granodiorite. The pegmatitic and the high- and medium-temperature hydrothermal minerals are found in the pegmatites themselves, which are intrusive into the granodiorite. The anchi-zeolites are confined to small veins cutting the granodiorite and pegmatite dikes. The zeolite minerals and prehnite are found chiefly in small veins that traverse the gneiss; but to a limited extent they are found in veins in the granodiorite and pegmatite.

The minerals of the magmatic stage are quartz, orthoclase, andesine, hornblende, magnetite, apatite, and sphene. Sericite, which is abundant in the granodiorite, is an alteration product of feldspar. The remaining minerals to be described are listed and arranged in the paragenetic table under their appropriate headings.

In the table, the association of the various minerals may be seen. It will be noted that there is considerable repetition of minerals in the various phases; under the section on descriptive mineralogy repeated occurrences of such minerals will be described under one title.

Descriptive Mineralogy

A detailed description of every mineral found at the Blueberry Mountain quarry will not be given. The common minerals, with which every-one is familiar, need simply a general statement as to occurrence. The minerals requiring fuller description are babingtonite, prehnite, albite, orangite, thorite, and allanite. The list of minerals follows the order in the paragenetic table with some modification due to repetition in the table.

Granodiorite. The mineral composition of the granodiorite is approximately as follows:

Hornblende	47%
Andesine	35
Orthoclase	5
Magnetite	5
Quartz	5
Apatite Sphene	3
Sericite (Alteration of the feldspars)	

The granodiorite shows strong alteration by hot hydrothermal solutions, resulting in the almost complete sericitization of the feldspars. The hornblende was derived from an original augite. Near vein and pegmatite contacts the hornblende is altered to babingtonite, the alteration starting in cleavages and occasionally replacing practically the whole crystal. Magnetite is accompanied by ilmenite; both are alterations of the original augite, the ilmenite being occasionally altered to leucoxene. The quartz is badly strained, reflecting the effects of earth movements.

Microcline and Orthoclase. These minerals occur as large crystals of pink color growing from the walls of the pegmatite dikes. The coloration is much more intense near the haloes and radiating cracks of radioactive minerals. They vary in size from relatively small crystals to some which are about a foot in diameter. Carlsbad twins attached to the walls at one end of the *c*-axis are common. The great majority of the crystals are, however, untwinned.

Biotite. This mineral probably occurred in medium-sized, plate-like crystals which are now completely altered to chlorite.

Hornblende. Masses of this mineral are sparsely scattered through the pegmatite. Though not in well-defined crystals, they exhibit typical amphibole cleavage. Implanted on the walls of small cross-cutting veins and cavities occur needle-like, pale blue-green crystals of an amphibole, probably tremolite.

Quartz. In the pegmatites themselves this mineral followed the crystallization of the feldspars, filling in the available space between the feldspar crystals. It is milky white in color. A second generation can be seen lining cavities in brilliant, small transparent crystals.

Magnetite. Rather small patches of magnetite occur in the pegmatite near the contact, and on the borders of zenoliths of granodiorite in the pegmatite. Small crystals, octahedron modified by dodecahedron, are also found in the secondary vein-cavities.

Sphene. This mineral occurs as large chocolate-brown masses with well-developed partings. It replaces feldspar and is itself replaced by chlorite. It is also found in small, highly lustrous crystals in the cavities.

Allanite. This radioactive mineral occurs rather abundantly in quartz and feldspar, in crystals ranging from 5 centimeters in length down to 3 millimeters. The matrix surrounding the crystals, whether of quartz or feldspar, shows radiating fractures which seem to have been caused by radioactivity. Unaltered, the mineral is black and vitreous; but when alteration has taken place it is dull grayish-black.

In powdered form under the microscope the mineral appears light olive-green with no cleavage. Some of the grains are isotropic; others are slightly birefringent; and still others show patches of gray interference colors. The grains are cut by minute veins of a mineral which has bright interference colors and a much higher index of refraction than the principal portion of the grains. These small veins may consist of epidote.

The index of refraction of the greater part of the allanite varies from 1.698–1.715. The grains which have the gray interference colors have an index greater than 1.71; the isotropic grains have a lower index. The birefracting material has an index between the two.

As far as can be determined microscopically the isotropic material appears to be an alteration product of the anisotropic allanite. This agrees with Goldschmidt's hypothesis[2] of the "metamict condition," the isotropic material being an alteration product of the original crystalline anisotropic allanite.

At Woburn the megascopic crystals of allanite show rude prismatic forms suggesting an anisotropic mineral with an alteration rim surrounding the fresh material. It would seem probable, therefore, that the alteration proceeded from the anisotropic allanite to the isotropic alteration product.[3]

Orangite, Thorite. These rare radioactive minerals occur scattered throughout the pegmatite in very small crystals. The tetragonal crystals, which are rarely a centimeter in length, have the first-order pyramid and the second-order prism. Like allanite they produce radial cracks in the matrix. The pure orangite is of a bright orange-yellow color, transparent and glassy.

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[2] Goldschmidt, V. M., *Geochemische Verteilungsgesetze der Elemente,* **III,** pp. 51–58, 1924.

[3] Tunell, George, The paragenesis of the pegmatite minerals of Winchester, Massachusetts, **1925,** (unpublished).

When powdered and observed under the microscope, the seemingly pure orangite was found to be made up of the following:

1. Isotropic fragments, colorless, with an index less than 1.70.
2. Cloudy and threaded patches in the first, colorless, faintly birefringent.
3. Isotropic, yellow, non-pleochroic, with index slightly greater than 1.70.
4. Black opaque flakes.
5. Zircon fragments, some of which are altered to cyrtolite.[4]

It is evident that the orangite at Woburn is not a pure mineral but a mixture. Originally orangite most likely formed with zirconium replacing a portion of the thorium. The black opaque flakes may consist of a sulphide which has been introduced at a later time. The pure orangite is represented by the yellow isotropic grains which have an index greater than 1.70.

It appears probable that orangite containing some zirconium formed under certain definite conditions; that under these conditions the mineral is perfectly homogeneous and stable; that when the equilibrium conditions changed the mineral became unstable and formed zircon and orangite; that with alteration by hydrothermal solutions some of the remaining orangite altered to thorite, the thorite to an undetermined substance, and the zircon to cyrtolite.

Epidote. This mineral is especially abundant throughout the quarry. It occurs in two generations, the first in pegmatite, where it forms crystallized masses of dark green color, often a foot in diameter. The crystals usually radiate from a center, appearing to replace feldspar at times and again crystallizing on the faces of the feldspar. The great abundance of this mineral warrants the use of the term "unakite pegmatite" for the pegmatites of this quarry. The epidote has the following composition as determined by its optical properties: $\beta = 1.752$

$$27\% \quad (H\,Ca_2\,Fe_3\,Si_3\,O_{13})$$
$$73\% \quad (H\,Ca_2\,Al_3\,Si_3\,O_{13})$$

It contains 12% Fe_2O_3. A second generation is found in small veins and cavities that traverse the pegmatites and the granodiorite. Here the epidote is in fine clear transparent crystals of light yellow-green color. The crystals are particularly well developed in simple combination. As far as could be determined the composition of the second generation of epidote is the same as the first.

Albite (variety cleavelandite). Fine white cleavage fragments of this mineral, with prominent albite twinning, occur as an alteration product of orthoclase and microcline. A second generation of albite consists of small transparent crystals attached to the walls of small veins. These

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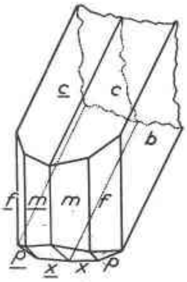
[4] Noble, James A., The pegmatites of the Winchester Highlands Quarry, Blueberry Mountain, Woburn (unpublished).

crystals are elongated parallel to [100] and are sometimes twinned (Fig. 1).

Tourmaline. One small, irregularly crystallized mass of this mineral was found. It is black in color but under the microscope shows a deep dirty green pleochroism. It is replaced by albite of the high-temperature hydrothermal phase, but the relationship to the other minerals of this phase could not be ascertained.



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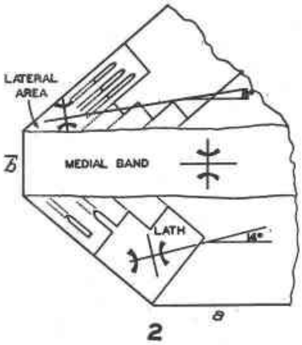

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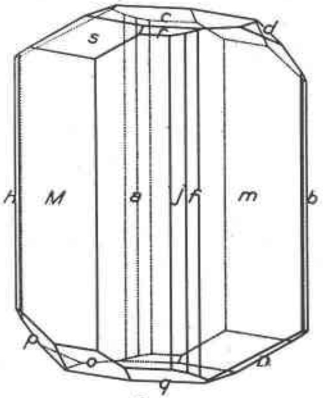

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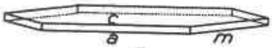

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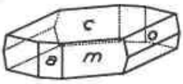

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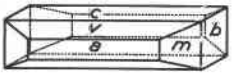

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FIG. 1. Albite; typical crystal twinned on (010) and elongated [100].

FIG. 2. Prehnite; fragment of a crystal showing hourglass structure and the optical orientation in several segments. After unpublished notes by G. Tunell.

FIGS. 3–5. Prehnite; typical habits.

FIG. 6. Babingtonite; typical doubly terminated crystal.

Chlorite. This mineral is found as an alteration product of biotite and epidote. In the latter mineral it sometimes completely replaces the epidote. The appearance is most striking when it forms solid masses, several inches across, of green to blackish green color and dense, scaly texture. It is seen as an alteration product of sphene. Another generation forms in small veins and cavities, as minute six-sided crystals of a deep blue-green color. The chemical character of these chlorites was not determined.

Pyrite. Large ill-defined crystallized masses occur in the pegmatite. It varies in color from silver-white to light yellow. A second generation of pyrite forms beautifully crystallized individuals in which rare forms are to be seen. Besides the cube and octahedron, there are developed the dodecahedron, a diploid, and a trapezohedron.

Molybdenite. One small crystallized mass has been found as a pegmatite mineral.

Adularia. This mineral is found in the small veins and cavities lining the walls in small, brilliant, transparent crystals.

Chalcopyrite. Small crystals of this mineral are found growing on the second generation pyrite.

Garnet (andradite). This mineral occurs in poorly crystallized individuals of a wine-red color.

Calcite. There appear to have been three generations of this mineral characterized by:

1. Flat rhombohedrons with very subordinate base and prism.
2. Negative unit rhombohedrons with very subordinate base.
3. A deposit of a thin crust on the crystals exhibiting the negative unit rhombohedron.

It should be noted that the small veins are filled with calcite; it is necessary to etch all specimens with dilute hydrochloric acid before the earlier minerals are revealed.

Prehnite. The fine crystals of this mineral are one of the features of the Blueberry Mountain quarry. It occurs in most of the small cross-cutting veins in the granodiorite, pegmatites and gneiss. Two generations are recognizable, the first occurring as bluish-green crusts on the walls of the small veins. The surface of the crust is composed of swarms of very small radiating crystals forming half rosettes. In other places they have grown in such a manner as to form caterpillar-like aggregates. Individual crystals occasionally project from these masses so that it is possible to measure them. Figure 4 illustrates a typical crystal; a rarer habit is shown in Fig. 5. Prehnite crystals of a second generation are attached to babingtonite and other minerals; they are transparent and platy with very simple form (Fig. 3).

Actually the prehnite crystals are complex in structure, consisting of several segments forming a rather regular pattern when seen in polarized light. From a study of the optical orientation,[5] the various segments appear to be aggregates of subparallel plates. In general they curve upward on all sides and are slightly rotated on the *c*-axis.

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[5] Tunell, George, Notes on the crystallography of prehnite (unpublished).

A detailed study of many crystals brings out the fact that the different segments are oriented in various ways. Figure 2 shows the arrangement of the orientation of the medial band, laths and lateral areas. The laths are embedded in the lateral areas and penetrate them at a low angle from the upper surface to the lower. From the optical evidence it is apparent that not only are the crystals made up of segments in a plane parallel to (001), but that normal thereto the crystal is composed of layers which are rotated 90° to each other, with the exception of the medial band which appears to act as a normal orthorhombic crystal. This is the typical "hourglass" structure described by Shannon.[6]

Babingtonite. Particular interest lies in the abundance of this rare mineral. While it has been found in quarries within a few miles of Winchester, the Blueberry Mountain quarry is the most abundant source of this mineral yet discovered. Babingtonite forms black triclinic crystals with submetallic luster; they range in size from one-tenth of a millimeter to several millimeters, occasionally reaching one centimeter. The crystals are typically short columns with simple terminations; they have been fully described by Palache.[7] Further details will be reserved for a forthcoming account of an *x*-ray study of the species which indicated a new orientation. Figure 6 represents a typical crystal of babingtonite from Blueberry Mountain; the forms, in the new setting, are: $c(001)$, $b(010)$, $a(100)$, $m(110)$, $f(210)$, $j(310)$, $M(1\bar{1}0)$, $h(1\bar{2}0)$, $d(011)$, $n(0\bar{1}1)$, $r(101)$, $q(\bar{1}01)$, $s(1\bar{1}1)$, $o(\bar{1}11)$, $p(\bar{1}21)$.

Sphalerite. Small colorless highly lustrous crystals in parallel growths on prehnite crusts.

Heulandite. Small twinned individuals of this mineral are found coating vein walls and interspersed among calcite crystals.

Stilbite and Laumontite. These occur in the same manner.

Analcite. Only found as quartz pseudomorphs in small crystals. The appearance of these pseudomorphs is most striking. They occur as slightly rounded trapezohedrons about 2 millimeters in size, forming hollow shells of a delicate salmon pink. When touched with a needle point they immediately disintegrate. It is surprising they should have survived blasting operations.

Hematite and Limonite. Hematite occurs in small platy crystals ar-

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[6] Shannon, E. V., The mineralogy and petrology of intrusive Triassic diabase at Goose Creek, Loudoun County, Virginia: *Proc. U. S. National Museum*, **66**, art. 2, pp. 62–68, 1924.

[7] Palache, C., and Fraprie, F. R., Contribution from the Harvard Mineralogical Museum, XII: 1. Babingtonite from Somerville, Mass.; 2. Babingtonite from Athol, Mass.; *Proc. Am. Acad.*, vol. **38**, pp. 383–393, 1902. Palache, C., and Gonyer, F. A., On babingtonite; *Am. Mineral.*, vol. **17**, pp. 295–303, 1932.

ranged in rosette-like patches altering to limonite. These two minerals are of supergene origin.

DISCUSSION

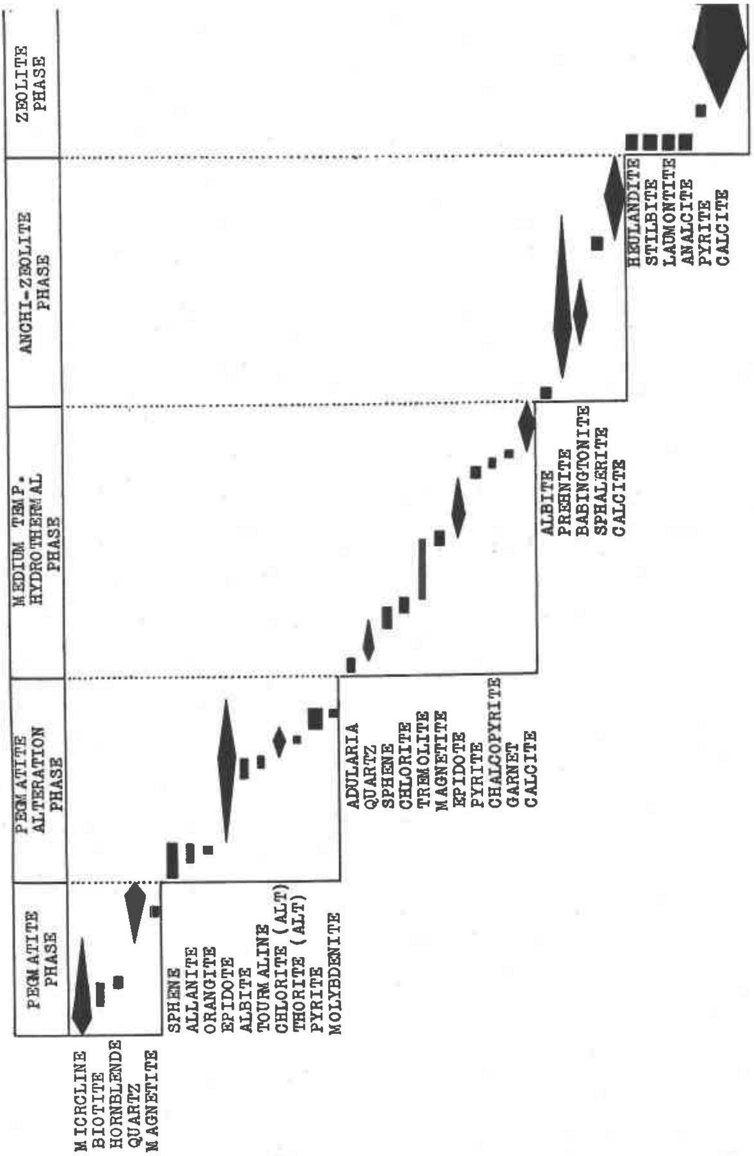
The several phases of hydrothermal activity are not distinct periods; they represent convenient stages in a continuous period in which the temperature of the fluids gradually decreased. The high-temperature hydrothermal phase, which corresponds to the pegmatite-alteration phase of the paragenetic table, represents temperatures above that of the inversion point of high to low quartz. The medium-temperature hydrothermal phase covers intermediate temperatures. The anchi-zeolite, zeolite and weathering phases represent temperatures ranging down to atmospheric.

Since earth movements appear to have taken place over a long period of time, small veins may be found representing various stages of decreasing temperature. In some veins only the pegmatite minerals are present; in others a variety of hydrothermal minerals appear, while others contain only zeolites.

During or immediately after the crystallization of the pegmatites, hot fluids from the magma chamber rose along the channels through which the pegmatite magma had passed. While these channels were the easiest means of exit for the fluids, they were not the only ones. Undoubtedly there were new fractures developed by the forceful ejection of the pegmatite magma, permitting the fluids to emanate through the granodiorite. The intense alteration of the minerals of the granodiorite was no doubt due to such emanations. The attack of these hot fluids, rich in mineralizers, produced profound alteration on the pegmatites. The microcline and orthoclase were in part altered to sphene, allanite, and orangite. Toward the middle of this phase, when the fluids had somewhat cooled, microcline and orthoclase were still further altered to epidote; sphene, by an exchange of titanium for iron, was altered to epidote; allanite remained unchanged, but the impure orangite probably changed to form some zircon, orangite, and thorite. Near the end of this period any biotite which had formed in the pegmatite stage was entirely altered to chlorite. Epidote was chloritized, and the microcline and orthoclase albitized. New minerals formed at this time were pyrite and molybdenite.

As the temperature gradually decreased, the minerals which were stable at a higher temperature became unstable. Minerals still present in the liquid were partially dissolved. A redeposition of the dissolved minerals occurred and a series of new minerals were formed as a result of chemical reaction. Minerals occurring in a second generation are epidote, albite, adularia, sphene, chlorite, magnetite, pyrite and quartz.

PARAGENETIC TABLE



The various phases are divided horizontally into spaces which show roughly the relative length of each phase. It should be understood that there is no such break in the sequence, but that these divisions are made for convenience in description.

The lozenge shapes are used where the abundance of the mineral and the clarity of the sequence is sufficient to establish an approximate maximum of deposition. The rectangles are used either when the sequence is not clear or the amount of the mineral present is very small.

The size of the rectangular and lozenge shapes indicates the relative abundance of the minerals in any one phase, but not in adjacent phases.

Tremolite fibers are included in this class since they were possibly derived from the hornblende of the pegmatite. New minerals that were formed are garnet, prehnite, chalcopyrite, babingtonite and calcite.

At this time calcite was formed in negative unit rhombohedrons. The cavities around some of the crystals were then filled with a mixture of the following minerals:

Babingtonite	75%
Amphibole fibers	10
Calcite	10
Orthoclase Albite Quartz	5

The result is a dark fine-grained mass filling the spaces between the calcite crystals. The babingtonite and tremolite fibers are in well-defined crystals; the remaining minerals form a mass of irregular grains. Whether this represents a sudden cooling of a liquid in which the babingtonite and tremolite fibers were floating is not clear. In the zeolite phase, pyrite, heulandite, stilbite, laumontite and analcite were formed, the solutions travelling beyond the confines of the granodiorite and reaching into the overlying gneiss.

SUMMARY

The minerals of Blueberry Mountain are explained in terms of a magmatic sequence—granodiorite, granite, aplite and pegmatite, followed by two principal periods of hydrothermal activity during which many minerals, including the uncommon species allanite, orangite and babingtonite, were deposited in the pegmatites and in veins cutting the pegmatites and the surrounding rocks. The hydrothermal fluids appear to have attacked the pegmatite minerals, causing partial or complete alteration, and to have deposited new minerals some of which were again modified by later and cooler solutions.

Points which the writer believes to be still in doubt are: the relation of the parallel and echelon arrangement of the pegmatites to tension cracks caused by torsional stresses; the possibility of leaching and lateral secretion having played some part in the mineral formation; and the origin of the abundant babingtonite.

ACKNOWLEDGMENTS

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