OCCURRENCE AND ORIGIN OF BABINGTONITE AND OTHER MINERALS FROM QUABBIN AQUEDUCT, MASSACHUSETTS

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Abstract

The suite of minerals from shaft 10 of the Quabbin Aqueduct is of more than usual interest, owing not only to the number of species that are present in the small veins and to the excellence of the minute crystals, but also to the presence of babingtonite at another locality in Massachusetts which gives the state 10 of the 14 known occurrences.

The question of origin is also one of special interest for the associated minerals, which with the exception of the feldspars and possibly the amphibole and mineral *X*, are characteristic of the mineral associations found in veins of the Connecticut Valley diabase of Massachusetts. As similar associations are not the usual products of residual solutions of acid magmas, the writer believes the solutions to have been derived, in their major portions at least, from very late fractions of a basic (gabbroic) magma.

The Quabbin Aqueduct, approximately 13 by 15 feet in cross-section, was driven between a point, shaft 1, on the Quinapoxet River near its entrance into Wachusett Reservoir, which is nine miles north of Worcester, and Quabbin Lake, a distance of 24 miles almost directly west. The tunnel is located at a depth of approximately one hundred to five hundred feet below the surface and transects the various schists, gneisses and igneous rocks at angles close to 90° to their strike. The excavations along the tunnel were conducted from a series of vertical shafts numbered from east to west. Shaft 10, from which the minerals were obtained, is located along Moose Brook at a point 2$\frac{4}{5}$ miles N 44° E from Hardwick, Massachusetts.

The formation to the west of shaft 10 to shaft 11 consists entirely of Hardwick granite. This material is described by Emerson (1, p. 238) as being:

> . . . almost everywhere a black granite gneiss but in several small central areas what seems clearly to be a deep-seated core is exposed. . . . It is low in quartz and rather feldspathic, containing generally orthoclase, a little plagioclase, much biotite, much magnetite, hypersthene, zircon and allanite but no graphite or fibrolite.

To the east of shaft 10 the tunnel penetrates approximately 1600 feet of Hardwick granite, 2625 feet of Brimfield-Ware schist, 1225 feet of Coys Hill granite and then remains in Brimfield-Ware schist to shaft 9 for an additional distance of 9650 feet (2, Figs. 8D, 8E, 8F).

Emerson (1, p. 68) describes the Brimfield-Ware schist as:

> . . . the most marked and most widely distributed of the metamorphic formations assigned to the Carboniferous. The rock is a uniform coarse red-brown muscovite schist containing much biotite, fibrolite, and graphite and so much pyrite that it is wholly rusted in many of the deepest openings.

Regarding the Coys Hill granite, Emerson (1, p. 240) says:

> It is a regularly sheeted very coarse porphyritic microcline granite gneiss, in which the flat carlsbad twins are generally 2 to 4 inches square and three-fourths of an inch thick, and many of them are so closely set that there is little space for the coarse dark biotite-garnet ground mass, which winds in and out among them. These crystals have generally a granulated border from incipient crushing, which increases in thickness at the expense of the central crystal and is drawn out in the planes of the banding so that they form eye-like spots and finally complete crushing produces a medium-grained granite.

Diabase Dikes

At a point 4800 feet east of shaft 9 a diabase dike, 175 feet wide, was penetrated by the tunnel excavation. This is the only reference to basic intrusives (2) across the west end of the tunnel location.

As the fragments of the mineral-bearing veins occurred on the surface of the large dump after the excavating work had ceased, and after a part of the dump material had been crushed for the concrete mixture for the tunnel lining, it is somewhat uncertain as to the exact position of their original occurrence. It is reasonable, however, to believe that they originated about midway between shafts 9 and 10, or 10 and 11. The former location being in the Brimfield-Ware schist while the latter is in the Hardwick granite. As the veins occur in a pinkish granite, one may, therefore, assume that the point of occurrence is in the Hardwick granite about 1¼ to 1½ miles west of shaft 10.

Description of the Veins and the Granite Wall Rock

The majority of the veins are very small, usually less than ¾ inch across. One or two fragments of a vein-breccia less than 2 inches across were found. Unless the veins are very small (⅛ to ¼ inch) they are seldom completely filled but contain numerous cavities lined with minute crystals, often of superb quality.

A megascopic examination shows that the wall rock is composed, in general, of an equi-granular medium grained granite which consists of both pink and light colored feldspar which reach a maximum size of ¾ inch. Quartz occurs as light-grayish to white colored grains. The dark constituents consist chiefly of chlorite, magnetite and sphene. The chlorite represents altered biotite which is an important mineral of the Hardwick granite and is the main contributor to the "black" color of Emerson's description. Near the veins some epidote occurs as grains while at times it completely fills very small fractures which traverse the granite. In some specimens the chlorite becomes an abundant constituent and the rock becomes rather dark in appearance. In such specimens the feldspar is usually light-colored and the grain of the rock becomes finer. The chlorite and the other constituents are usually more or less banded and give the rock a gneissoid appearance. In addition, the following minerals are readily distinguished in hand specimens but do not always occur in thin sections: magnetite is probably the most abundant of these and is associated with the chlorite; sphene is rather conspicuous in a few specimens and common in most. Some specimens contain a number of allanite grains which stain the adjoining minerals, while a few grains of hornblende and an opaque black non-magnetic mineral were also observed.

A microscopic study shows that the three most abundant constituents are plagioclase, potash feldspars and quartz which produce an allotriomorphic medium-grained texture. The plagioclase is strongly altered to a very fine grained sericite. In some grains a rather fresh core of the plagioclase remains. The potash feldspars, orthoclase and microcline, are unaltered. The quartz contains many dust-like inclusions often in poorly defined bands; it also may show numerous incipient fractures arranged en echelon. The feldspars and quartz contain acicular crystals which are probably apatite. The biotite has been completely altered to chlorite. It occurs chiefly around the grains of the feldspar and quartz and usually in streaks. Whether the alteration is due to the vein solutions or to other more widespread phenomena could not be readily determined and was not investigated. Associated with the chlorite, which is strongly pleochroic from a brownish-yellowish green to deep emerald green, are small rounded grains of apatite. A few grains of zircon are present and these produce pleochroic halos in the chlorite.

The field geologists for the Water Commission (2) have recorded, in considerable detail, data concerning the character and structure of the rocks traversed by the tunnel. This information has been made available in the form of a descriptive elevation along the north wall together with a floor plan of the tunnel. From the section between shafts 9 and 10, and 10 and 11 one finds that numerous small pegmatites of various textures appear in all the formations and these pegmatitic phases vary in size from stringers and lenses to dikes more than five feet in thickness. The dip of the foliation is at a low angle of 10 to 25 degrees to the west.

The writer was unable to find any mention in this data of the occurrence of mineral veins of the type described here, which may be due to their small dimensions and while underground would be obscured by mud and rock dust. On the dump, after a rain, they would, however, readily attract the attention of mineral collectors.

Paragenesis of the Vein Minerals

The first increment of material deposited on the wall rock frequently consisted of additions to the quartz and feldspar already a part of the granite. These additions were not abundant and consisted chiefly of developing crystal faces, on earlier grains, often in parallel growth. Only rarely did these minerals continue to grow inward toward the center of the vein for any appreciable distance. Occasionally there are splendid crystals of albite which are only lightly attached to the walls so that they can be removed.

The first substantial deposition everywhere in the fractures consists of epidote which varies from a light yellowish-green to dark greenish-black. Scattered crystals of fluorite rest upon the epidote as well as upon the original wall-rock minerals in which instance they are often partly, and at times completely, covered with epidote. The fluorite is not abundant enough to completely cover the epidote over any appreciable area. Babingtonite frequently completely covers large areas of epidote and the scattered crystals of fluorite as well. Following the babingtonite in order of deposition are calcite and selenite, which are abundant enough to cover the preceding species; apophyllite sometimes completely covers babingtonite. Selenite is always the last mineral to be deposited. It frequently is present only as solution remnants scattered over large areas which indicates that it was originally much more abundant. Calcite likewise has been removed to a considerable extent by solution, and where these minerals do not appear in the veins it is not at all safe to assume that they were not present. One would probably be safer in assuming that both selenite and calcite were originally present in most of the veins unless the veins are small and completely filled by the earlier minerals.

The parts of the veins where deposition has been light one may find several of the earlier minerals attached to the walls singly or in small

Table 1. Paragenesis of the Vein Minerals

Wall Rock Minerals	Vein Minerals						
1	2	3	4	5	6	7	8
Quartz Albite Chlorite (of the wall rock) Allanite Magnetite Orthoclase Sphene Hornblende Microcline	*Albite*[a] Adularia Quartz	*Epidote* Fluorite (colorless to amethyst) Prehnite*	*Fluorite* (blue) Amphibole (fibrous) Galena* Sphalerite* Pyrite* Chlorite*	*Babingtonite* Mineral X* Thomsonite*	*Apophyllite* Heulandite Stilbite	*Calcite*	*Selenite*

[a] The minerals in italics are the most abundant and persistent in their relationship to one another.

* In the specimens collected, these species were not covered by later minerals and hence may properly come under a later group, if the sequence were complete in all specimens.

groups without supporting later minerals. One may readily give a more inclusive or composite paragenetic picture and introduce the rarer species in the sequence as shown in Table 1.

With the exception of fluorite, the minerals in columns 4, 5, 6, 7 and 8 are sometimes absent. Minerals in columns 5, 6, 7 and 8 may be present singly or in combinations, except that calcite was not seen in association with the zeolites in such a manner that its sequence with respect to these minerals could be certain. However, rhombic cavities of presumably mineral X in calcite occur in one specimen which would place it earlier than calcite, and as the zeolites are not directly associated with calcite they too may be earlier in the general sequence as indicated. Calcite may belong in column 6 but its presence there could not be confirmed.

Origin of the Minerals

The origin of the minerals from shaft 10, except for adularia and albite, which are very closely associated with the minerals of the granite wall rock, is probably best determined by considering the probable origin of the solutions from which babingtonite in other occurrences crystallized. From thirteen (3, p. 302) out of the fourteen[1] authentic occurrences of babingtonite, seven are associated directly with veins in or at the contact of diabase, two occur with pegmatite granite, two with veins in gneiss and one each in granodiorite and diorite. Even the occurrence of babingtonite in pegmatite granite and in veins in gneiss does not exclude the possibility that the mineral solutions in these instances may have been mixed and that the essential constituents which were responsible for the formation of the babingtonite were derived from magma fractions, or segregations, of a far more basic character than the enclosing rock. *In each of the fourteen occurrences the mineral calcite is present and it may be the real marker in determining the origin of the solutions* which, in all cases, are undoubtedly the end product of the crystallization of some magma, or they may possibly have been produced during severe metamorphism as an end product of recrystallization during which process the water of crystallization of earlier minerals has been expelled together with some of the more soluble materials present. The end products of crystallization of acid magmas result almost universally in producing pegmatites, pegmatitic phases in the solidified parts of the magmas, or as mineral veins usually of an acid character and *exceptionally free from babingtonite.* The first two types of deposits unless contaminated from the enclosing rocks, or from other solutions, are comparatively free

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[1] The fourteenth and as yet undescribed occurrence is in veins in the Holyoke diabase at the Amherst "Notch Quarry" about midway between Amherst and South Hadley, Massachusetts.

from calcite instead of this mineral being always or even frequently present. While calcite is somewhat more abundant in the mineral veins derived from acid magma solutions than in the pegmatites, nevertheless, it is not a mineral that is *always* present, even in small amounts. As the magmas become more basic, carbonate becomes more abundant in the late fractions and in the residual solutions. Veins formed from solutions from basic magmas usually contain calcite as one of the minerals. Wagner (5, p. 198) and Daly (6) describe carbonate dikes associated with the peridotite of the Premier Diamond Mine, Transvaal, South Africa. Small carbonate dikes up to two inches across occur in the Holyoke diabase[2] at the Amherst Notch Quarry where they represent very late fractions of the gabbroic magma.

The nearest recorded diabase dike along the tunnel is nearly a mile east of shaft 9 and at least two to three miles from the nearest possible occurrence of the minerals, and in addition the schistosity of the formations dips at a low angle of 15 to 20 degrees to the west from the dike and toward the location of the mineral veins. Hence, it is hardly possible that the magma of this dike could have supplied the necessary solutions.

The most important data concerning the occurrence of babingtonite is that at least half of the occurrences of the mineral have been certainly derived from late diabase or gabbro solutions; and some of the other occurrences are closely associated with granodiorite, and diorite, rocks which are near relatives of gabbro. It is apparently important that one always finds calcite associated with babingtonite. With these pertinent facts bearing on the origin of babingtonite in other deposits, one may at least consider three possible sources for the mineral solutions that produced the minerals obtained from shaft 10.

For the first, one may consider the solutions as originating from a gabbro, or closely related magma, which crystallized in some unknown position not too remote from the occurrence of the mineral veins. Fracturing and brecciation of the granite about the intruded gabbroic magma provided fissures for the passage of hydrothermal fluids from the crystallizing magma, and also provided many voids for the development of the superb crystals that they now contain. It is known that a few isolated occurrences of diabase and other basic rocks occur to the east of the Connecticut Valley (1, p. 272) and many others may occur at unknown places within the rocks along the line of the tunnel.

As an alternative theory one may prefer to have the mineral-bearing solutions originate as late fractions of some basic differentiate of the

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[2] The fine-grained carbonate dikes and the coarse-grained phases of the Holyoke diabase at the Amherst Notch Quarry are being studied in detail.

granite, or a portion of the granite rendered initially basic by the assimilation of basic sediments or other earlier basic rocks.

One may also consider as a third possibility a theory which would account for the hydrothermal solutions as originating from (*a*) the crystallization of the normal granite, or (*b*) from the more basic parts which are quite rich in the black minerals biotite and magnetite; and (*c*) from the pegmatites associated with the granite or the pegmatitic phases of the granite.

If the solutions had originated according to the second or third conditions it would appear to the writer that babingtonite and the associated minerals should be of much more frequent occurrence in the Hardwick granite. Due to the lack of this more frequent occurrence, or the lack of knowledge concerning such occurrences, the writer tentatively considers the hydrothermal solutions to have originated from the crystallization of some gabbroic, or closely related magma, not too distant from the mineral veins and that the dynamic disturbances associated with the intrusion provided the necessary fracture system to convey the solutions and also provided spaces for the deposition of the minerals.

Brief Description of the Vein Minerals

Owing to the many splendid small crystals that occur among the species described below, a more detailed description of the morphology of many of them will follow at a later date. The following description of the minerals is arranged alphabetically rather than according to their abundance.

Adularia. Adularia is not very abundant and occurs chiefly as reddish to colorless crystals attached to the walls. The faces are usually dull and the body of the crystals contain many inclusions. They vary in size up to 3 mm.

Albite. Many splendid crystals of albite occur next to the granite walls to which they are usually firmly attached. Their development is chiefly parallel and close to the wall rather than projecting into the cavities. Occasionally well-developed crystals extend sufficiently far into the cavities so that they can be removed. They are often water clear and have brilliant faces. Their size is usually less than 3 mm.

Amphibole. A white to light cream colored fibrous amphibole consisting of small "pads" of extremely fine filamentary particles matted together and resembling "mountain leather" in appearance occurs on several specimens. It has a mean index of about 1.65 and occurs overlying epidote or between epidote and calcite.

Apophyllite. The largest and most conspicuous of the well-formed crystals are apophyllite. They vary in size from minute microscopic ones to slightly over a centimeter across. The smaller ones sometimes approach equidimensional proportions and are water clear while the larger ones are tabular and of a milky white color. They are next in abundance to babingtonite and in one specimen a large part of the babingtonite is completely covered. The corners of most of the crystals are truncated by the bipyramids.

Babingtonite. This mineral is probably next to epidote in abundance and frequently occurs as a continuous covering over an earlier deposit of epidote, which often in turn completely covers the walls. The crystals of babingtonite are short prismatic and usually possess brilliant faces. The larger crystals are jet black in reflected light while the smaller ones are of a distinct reddish-brown color. The size of individual crystals varies from less than a hundredth of a millimeter to 1½ millimeters. Several masses of babingtonite up to a centimeter across were observed. These are probably composed of compact granular aggregates.

Calcite. Calcite is among the more abundant minerals, but seldom occurs in good crystals for those present are usually strongly etched or even partly dissolved. Comparatively large masses occur covering epidote and small crystals are superimposed on babingtonite. One specimen of calcite contained rhombic cavities of an earlier mineral more soluble than calcite. The angles of the cavities are difficult to evaluate on account of their small size and the irregular enlargement by solution. These cavities are probably due to the mineral described below as mineral X.

Chlorite. As a distinct vein mineral chlorite is very rare. It was found in one specimen as clusters of extremely minute crystals covering adularia, quartz and lavender fluorite. It is strongly pleochroic in green and yellowish-green. Shreds of chlorite from the wall rock also project into the fissure for a short distance. The vein chlorite may represent material dissolved from the walls and redeposited in the fissure.

Epidote. Epidote is the most abundant mineral present and is readily recognized by its characteristic yellowish-green color in the smaller crystals and by the light greenish-yellow powder of the larger ones when crushed. The larger dense areas and the large crystals often appear dark green to black. They vary in size from small microscopic ones up to 2 mm. for those of more or less equidimensional proportions. In only two specimens did the habit vary in which instances the crystals formed small groups radiating from common centers. The epidote is often overlain by babingtonite, selenite, calcite and to a much less extent by fluorite. The equidimensional crystals are of a superb character for morphological studies which are now in progress.

Fluorite. The first deposition of fluorite occurred simultaneously with epidote and continued later, producing well-developed crystals superimposed on the epidote. Fluorite varies considerably in its habit. It is commonly present as octahedrons more or less rounded and in irregular masses varying from colorless to a deep lavender color. On some specimens the octahedrons are very sharply developed and have glistening faces. Occasionally the fluorite is of a deep blue color and the octahedrons are then modified by cubes and the trisoctahedral forms.

Galena-Anglesite. Two crystals of galena were found resting on albite, one was a well-developed unmodified octahedron. A white coating, which is soluble in nitric acid without effervescence, surrounded the crystals. It is probably the lead sulphate, anglesite.

Heulandite. This is one of the less abundant species. It occurs sparingly on a few specimens. In one instance it consists of a group of fine transparent crystals about ½ to 1 mm. in size.

Limonite. The veins are almost free from the effects of oxidation and only a few "rusty" spots occur where minute crystals of pyrite have altered to limonite.

Prehnite. Prehnite was observed on only one specimen which consisted of brecciated granite loosely cemented by the vein minerals. Numerous open spaces remained for the development of many fine crystals of epidote, fluorite and albite. With these the prehnite occurs as one of the earlier to crystallize. It consists of the characteristic bunch-like or spherical aggregates, and is of a slight bluish-green color.

Pyrite. Sulphides are very rare in this mineral occurrence. Only a few small crystals of pyrite were observed usually unaltered and consisting of cubes modified by pyritohedrons.

Quartz. As a strictly vein mineral, quartz must be considered to be among the less plentiful species. Although the wall rock contains an abundance of quartz, the typical terminated quartz crystal projecting into the fissure is indeed rare. It appears that the quartz grains in the wall rock started a renewed growth by developing crystal faces in parallel position and remaining close to the vein fractures in the same manner as albite.

Selenite. At one period, selenite was much more abundant than at present as much of it has been removed in solution, for the material now present is clearly the remnants of solution processes. All crystal forms, if they ever existed, have been completely removed. The material is white to transparent in color and forms a protecting cover for epidote, fluorite, stilbite, babingtonite apophyllite and mineral *X*. Where the selenite has been dissolved from these minerals they remain as splendid brilliant crystals. The underlying minerals may be readily obtained on account of the softness and easy cleavages of selenite, together with the lack of adhesion of the selenite to the earlier minerals.

Sphalerite. A single greenish crystal of sphalerite was found on epidote. Its very high index, dodecahedral cleavage and optical isotropism easily distinguish it from other minerals.

Stilbite. A few specimens contained small groups of isolated stilbite crystals of a lath-like habit. Stilbite is contemporaneous with apophyllite and both are covered by selenite.

Thomsonite. A few nearly equidimensional crystals of thomsonite having a very faint pink color occur with epidote and mineral *X*. They do not have good crystal faces and were undoubtedly covered by selenite, the solution remnants of which adjoin the crystals.

Mineral X. The identity of this white, monoclinic mineral which occurs in very small amounts is in doubt. Its mean index of refraction is close to 1.507, it has a large optic angle and an extinction angle of nearly 40 degrees and a low birefringence. A few fair to good, but very small, crystals occur in and around selenite. It is hoped that sufficient material will be found to obtain the necessary information for its identification.

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