



A COMPLEX, GENTHELVITE-BEARING SKARN FROM THE PASSAIC PIT, STERLING HILL MINE, OGDENSBURG, NEW JERSEY

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In 2002 a trench dug in the Passaic open pit at the Sterling Hill mine exposed what is probably the most important occurrence of genthelvite in the United States. The rock shows evidence of a complex series of metamorphic events, with different mineral assemblages forming over millions of years.

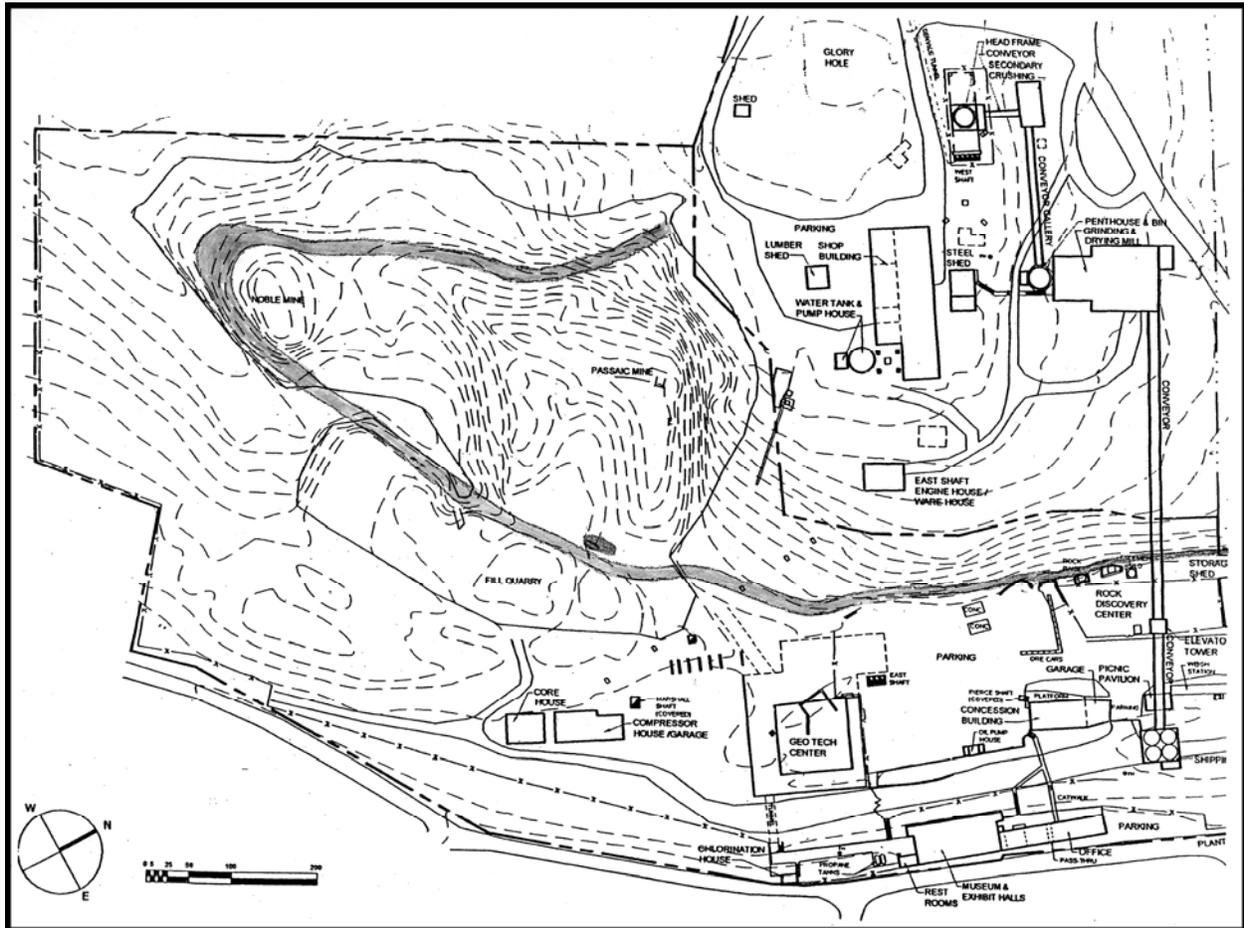


Figure 1. Map of the surface workings of the Sterling Hill mine, showing the Passaic and Noble pits, the trace of the orebody, the genthelvite trench, and mine buildings. The contour interval is five feet. Map prepared by Steven Misiur, Sterling Hill Mining Museum; location of the orebody and the trench by Earl Verbeek. Both limbs of the orebody dip about 55° to the east (bottom of the map), and the topography is steep and variable. The trace of the orebody as drawn is an attempt to show its approximate thickness and position rather than its projected outcrop on the plane of the map.

INTRODUCTION

The Sterling Hill zinc-iron-manganese deposit at Ogdensburg, New Jersey (Johnson *et al.*, 1990) is an ancient ocean-floor exhalative (hot spring) deposit that was deformed into an overturned isoclinal syncline and metamorphosed during the Ottawa orogeny, 1090-1030 Ma (million years ago). There is general agreement that metamorphism reached 750° C at 4-5 kb pressure, at 12-15 km (7-9 miles) depth of burial (Drake, 1990; Volkert, 2005). The highest stages of metamorphism were followed by a long period of slow cooling and erosion, and by late Precambrian time (about 650 Ma) the region was exposed at the surface. During this interval there was retrograde alteration of some of the rocks, including the pervasive hydrothermal

alteration of the Sterling Hill deposit, which Metsger *et al.* (1958) have compared to serpentinization. The deposit was worked for zinc from the 19th century until the 1980s; the accessible mine workings and the remaining mine buildings are preserved as the nonprofit Sterling Hill Mining Museum.

The overturned synclinal orebody dips eastward at about 55° and plunges to the north. At its southern end the nose of the syncline is exposed at the surface; here the Noble and Passaic open pits were dug in the 19th century to mine hemimorphite formed by the weathering of the primary ores (Fig. 1). In the summer of 2002, John Kolic of the Sterling Hill Mining Museum dug a trench that exposed pyroxene-rich metamorphic rock, hereafter termed *skarn*, part of the Pyroxene Zone of Metsger *et al.* (1958), on the northeastern margin of the Passaic pit immediately north of the road leading from the Fill quarry into that pit; detailed coordinates are given in Table 1.

Table I: Genthelvite trench location coordinates in different systems

UTM coordinates (two readings, different dates):

18T 0533141 E 4547963 N +/- 11 ft, WGS 84 datum
18T 0533142 E 4547966 N +/- 20 ft, WGS 84 datum

Lat.-Long:

For conversion purposes, an easting of 0533141 and a northing of 4547965 results in a lat-long reading of:

41° 04' 56.176" N latitude
74° 36' 19.620" W longitude

Approximate mine coordinates are 740N, 1410 W.

The skarn exposed in the trench contains a varied and complex suite of minerals, including bright green-fluorescing genthelvite (Cianciulli and Verbeek, 2003; Verbeek and Yeates, 2003). This skarn was heavily collected during 2002, and the trench became known to collectors as the “genthelvite pit,” although genthelvite is a miniscule part of the rock. The manganese-rich calcite of the skarn quickly developed the dark stain characteristic of Sterling Hill and Franklin calcite, and by 2003 it was difficult to distinguish the minerals present in the exposure. As of December 2008 the trench measured in excess of 13 meters long parallel to the trend of the orebody, 5.7 meters wide at its widest point (its average width was 5 m), and 2.7 meters deep at its deepest point. However, in March 2009 the entire area was excavated, and the trench as such no longer exists.

The eastern edge of the trench was about 4 meters stratigraphically below the footwall contact of ore as economically defined (i.e., below the lowest zone of abundant franklinite in calcite), but only an average of 1 meter below the orebody contact as mineralogically defined (i.e., below the lowest layer of disseminated franklinite in calcite). The trench was bordered on the west by the breccia fill of the Passaic pit and on the east by an overhanging ledge of rock composed of very coarse-grained calcite marble containing locally abundant gahnite crystals 2-5 cm across. Cutting in sharp discordance across this layer east of the trench was an irregular mass of black mica containing numerous clasts of coarse-grained calcite, presumably derived from the marble layer. The contact was irregular but sharp, and locally was at nearly right angles to the

compositional layering of the rock. This mass of mica was thickest near the southeastern corner of the genthelvite trench and pinched out northward. The marble near and beyond the northern part of the trench was cut by thin, irregular masses and stringers of black mica continuous with the main mass and roughly conformable to the compositional layering of the rock. The mica mass is here interpreted as the metamorphosed mud fill of a pre-Ottawan solution opening (part of an ancient cave system) in the Franklin Marble. A similar but larger mass of mica, containing clasts of calcite and garnet, is exposed along the east limb of ore just south of the parking lot at Sterling Hill; this mica mass cuts out an appreciable thickness of the ore.

The material excavated from the trench consists of highly weathered blocks of rock in a broad range of sizes, from small fragments several centimeters across to boulders more than two meters, in a groundmass of loose material generally containing much mica. Where exposed by excavation, some of the boulders show conspicuously rounded surfaces. The rock fragments and blocks in the trench have rough, discolored, highly weathered surfaces, with insoluble mineral grains standing in bold relief above the matrix calcite. The blocks of rock in the trench are in place in an overall stratigraphic sense, but are detached from one another and appear to be a marginal part of the solution-collapse rubble that occupies much of the Passaic pit. This rock and underlying “mud zone” (Metsger, 1990; Metsger *et al.*, 1958) are interpreted by one of us (ERV) as a solution-collapse breccia pipe. Underground mining and drill records show that this pipe-like body extended to a depth of more than 200 meters below the surface. It is uncertain how much the blocks exposed in the trench have moved relative to the east limb, but the amount of movement appears slight and does not affect the minerals and assemblages observed, which predate the formation of the rubble.



Figure 2. Augite skarn (9 cm): augite, garnet, bluish-gray calcite, trace sphalerite (above dime). University of Delaware specimen, Sharon Fitzgerald photo.

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A notable feature of the exposure in the trench is that it contains different kinds of rock. The normal rock, typical of the Pyroxene Zone, consists of pale bluish gray calcite and dark brownish green, nearly black (ripe olive) augite, with local bustamite, gahnite, franklinite, garnet, biotite/hendricksite, and sparse rhodonite (Fig. 2). This rock contains elongate masses of coarse white calcite about 1 meter wide, which appear to follow the trend of the normal rock rather than cutting across it. The white calcite contains coarse crystals of a green amphibole and pink rhodonite to 7.5 cm (Fig. 3) and a number of other minerals, including the genthelvite. Although there is substantial overlap between the two assemblages, they differ so markedly in appearance and mineralogy that they seemed worthy of detailed examination. In the discussion below, the two different assemblages are termed “the augite skarn” and “the rhodonite skarn.” Locally there are also minerals that appear to be of later, hydrothermal origin, and others that are clearly weathering products.



Figure 3. Rhodonite skarn (15 cm): rhodonite (pink), actinolite (dark green), calcite (white), minor willemite (brownish maroon) at bottom. Jeff Glover photo.

METHODS

A large suite of samples from the trench is preserved at the Sterling Hill Mining Museum, and local collectors have more; samples both from the museum and from private collections have been examined by ERV. More than 100 additional specimens (91 kg of rock) were collected by PBL in the autumn of 2002. These specimens were taken from the loose rubble of the trench, which largely covered the actual exposure. Although it was possible to sample a wide variety of minerals and assemblages, it was not possible to see their locations relative to each other. Minerals were first identified by sight, and the identifications were then confirmed by X-ray diffraction (XRD), using a computer-controlled X-ray diffractometer. Indices of refraction were measured on a few minerals as noted below, to help determine their compositions. Finally, samples of the amphibole, rhodonite and augite were examined using an energy-dispersive X-ray spectroscopy (EDS) analyzer attached to a scanning electron microscope. Data reductions were made using the built-in standards and programs of the unit, yielding semiquantitative analyses useful for comparing transition-metal ratios, but not accurate enough to be quantitative or to allow chemical formulas to be calculated.

MINERALS

Here we describe each mineral species observed in alphabetical order and in later sections discuss the assemblages to which they belong and the conditions under which they formed.

Actinolite $\text{Ca}_2(\text{Mg}, \text{Fe}^{2+}, \text{Mn}^{2+}, \text{Zn})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$

Semiquantitative microprobe analysis indicates that the green amphibole contains calcium, magnesium, iron, zinc and manganese but little aluminum or sodium, so it can be identified as actinolite. Crude crystals and cleavages of actinolite up to 10 cm in maximum dimension are fairly common in the rhodonite skarn (Fig. 4). One crude crystal measures $3.5 \times 4 \times 9$ cm along the *a*, *b*, and *c* axes respectively, and is broken across the *c*-axis. Most cleavages are much smaller, typically about 1.25 cm. Actinolite is dark green, with characteristic cleavage and splintery (“woody”) fracture. Actinolite is commonly associated with rhodonite and also occurs as small, oriented flakes that form rings near the outside of some rhodonite crystals. Locally it is seen as scattered, randomly oriented grains embedded in large masses of albite. EDS analysis shows the actinolite to be fluorine-free, unlike the tremolite and some hornblende of the Franklin Marble.

In numerous specimens the roughly equigranular augite of the augite skarn is partially and variably replaced by green actinolite, but the rock retains much of its original texture. Some specimens show a well-defined gradation from unaltered or little-altered augite-calcite skarn to rock where most of the augite has been replaced by a generally coarser-grained assemblage of actinolite, rhodonite, calcite, quartz and other minerals. Many specimens show veins containing one or more of the minerals calcite, rhodonite, albite, willemite and genthelvite bordered by narrow selvages (2-10 mm) where the augite of the original host rock is replaced by actinolite.

Locally, actinolite is intergrown with, and possibly replaces, rhodonite. In one specimen a single grain can be traced from pink rhodonite containing oriented intergrowths of minor green actinolite to solid actinolite, with cleavage traces of the original rhodonite visible in continuity through the transition. However, the reverse relationship also occurs, where a large (2 × 4-cm) grain of actinolite is almost completely enclosed by an irregular rim of rhodonite 1 cm thick.

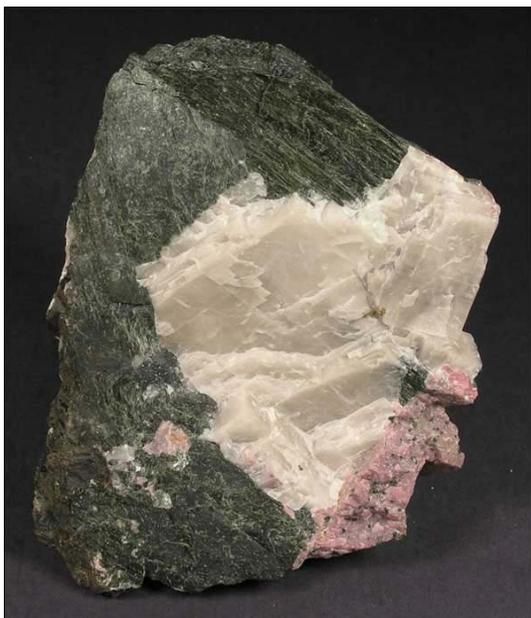


Figure 4. Coarse actinolite (11 cm): actinolite, white calcite, rhodonite with actinolite inclusions. Sterling Hill Mining Museum SHMM 201, Jeff Glover photo.



Figure 5. Augite (15 cm): augite including calcite in leopard rock or poikiloblastic texture. Earl Verbeek photo.

Albite $\text{NaAlSi}_3\text{O}_8$

White sodic plagioclase appears as a component of the rhodonite skarn with rhodonite, actinolite, calcite, quartz, willemitte, galena and genthelvite, and in veins transecting the augite skarn; based on indices of refraction it has been determined that this plagioclase ranges from albite to oligoclase. Some coarse-grained, anhedral masses are of large size: one measures $6 \times 8 \times 13$ cm and is an incomplete part of a single grain. Twin striations are commonly in evidence upon close inspection. Albite encloses a variety of minerals and rock fragments, including apatite in small, euhedral, prismatic crystals; calcite in red-fluorescing grains; genthelvite, locally in well-formed euhedral crystals, mostly tiny but locally as much as 2.1 cm on edge; titanite; and isolated, apparently brecciated fragments of augite-calcite “leopard rock” (see below under **Augite**).

Apatite $\text{Ca}_5(\text{PO}_4)_3\text{F}$

An apatite-group mineral, presumably apatite-(CaF), is common as small (1 cm or less), blue to greenish blue, euhedral to subhedral prismatic crystals embedded in actinolite, albite, calcite, galena, quartz, rhodonite and willemitte of the rhodonite skarn. The apatite fluoresces orange to brownish orange under shortwave ultraviolet light, as is typical of manganese-rich apatites from Sterling Hill (Fig 10). The daylight color, sharply defined hexagonal crystal sections, and fluorescence of this mineral are collectively distinctive.

Augite $(\text{Ca,Na})(\text{Mg,Fe,Mn,Al,Zn,Ti})(\text{Si,Al})_2\text{O}_6$

Much rock in the trench consists of ripe-olive-colored to black augite in equant to weakly elongate grains, 1-2 cm in maximum dimension, intergrown with gray to slightly bluish gray calcite (Fig. 2). This augite is commonly referred to as “jeffersonite” (Palache, 1935); it is chemically complex and contains significant zinc

and manganese. Small grains of blue-fluorescing sphalerite are a common associate; orange-brown, glassy garnet is present locally, and gahnite sparingly. The grain size of the augite in some specimens appears smaller than it actually is because of its poikiloblastic texture – individual grains of augite are host to abundant rounded grains of calcite, in addition to the matrix calcite that appears between the augite grains. This texturally distinctive material, known locally as “leopard rock” (Fig. 5), is popular among collectors for the attractively patterned red fluorescence of the manganese-rich calcite. Augite also occurs locally as bladed crystals associated with bustamite, rhodonite and white calcite in the rhodonite skarn.

Azurite $\text{Cu}^{2+}_3(\text{CO}_3)_2(\text{OH})_2$

Azurite is sparingly present as a minor weathering component of chalcocite. In one specimen, augite has been partially replaced by galena and by another dark mineral that is dull black and locally tarnished dark iridescent blue (possibly chalcocite; see below). In these areas, later alteration has produced dark blue azurite and green malachite, both quite prominent visually, the azurite, especially, having grown where carbonate was most readily available, along the edges of calcite grains embedded in the augite. In some specimens azurite forms thin coatings along cleavage surfaces in large calcite grains.

“Barite”

A late-stage mineral which occurs as thin, cream-colored coatings and as wispy veinlets along cleavage surfaces in other minerals, and which fluoresces bright yellowish-white to pale yellow in longwave ultraviolet light, is widely present at Sterling Hill. For years this mineral has been referred to by local collectors as “longwave barite,” but the identification was based purely on its fluorescence. Recent XRD analyses by Jim Van Fleet of Bucknell University (January 2009) show it to be calcite. This late-stage calcite is common in the trench, where much of the rock is highly weathered on exterior surfaces, and late-stage coatings and impregnations are common.

Biotite $\text{K}(\text{Fe},\text{Mg},\text{Zn},\text{Mn})_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2$

A dark brownish black member of the biotite family is an uncommon component of the augite skarn, wherein it is generally intergrown with garnet. Along the southeastern margin of the trench, the rock is a nearly pure mass of biotite in which are embedded clasts of calcite and local gahnite, as mentioned above. The distribution of biotite in the trench, and its absence from the retrograde assemblage, suggest that it is a component of the peak metamorphic assemblage in this area.



Figure 6. Bustamite, 20 cm: least altered bustamite mantled by rhodonite, with augite and bluish gray calcite. Mark Boyer collection, MB418, Earl Verbeek photo.

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Bustamite $\text{Ca}_3(\text{Mn,Ca,Zn})_3(\text{Si}_3\text{O}_9)$

Bustamite is uncommon but locally important. Dull, pale orange to gray masses of bustamite from 4 to 13 cm are invariably surrounded by rhodonite and quartz and are associated with bladed augite (Fig. 6, 16). These masses were identified in the field as bustamite, but XRD showed that they range from nearly pure orange bustamite to a gray, fine-grained mixture of bustamite, rhodonite, calcite and quartz. A sample of this mixture was very hard to cut into a thin section, as the section crumbled readily during preparation, but the patch that could be examined showed that all four minerals have a fine granular texture.

Calcite CaCO_3

Calcite is the most abundant mineral of both the augite and rhodonite skarns and forms the matrix for the other minerals; it makes up about half of the augite skarn and a higher proportion of the rhodonite skarn. The calcite of the augite skarn is pale bluish gray and fluoresces brilliant red. Cleavages up to 3.75 cm were observed in this study. The calcite of the rhodonite skarn lacks the bluish tint but is also strongly fluorescent. The average grain size of the white calcite is coarser than that of the blue, and cleavages of white calcite as much as 10 cm across were observed. One specimen shows an abrupt transition between bluish gray, augite-bearing calcite and white, actinolite-bearing calcite

Chalcocite Cu_2S

Augite in many specimens is variably intergrown with galena, and in some cases small grains of chalcocite appear to be present as well: the tentative identification is based on their dull black color, local iridescent blue tarnish, and alteration to azurite and malachite. In one specimen the supposed chalcocite is present in a sufficiently large mass that it could be readily scratched with a needle.

Franklinite $(\text{Zn,Mn}^{2+},\text{Fe}^{2+})(\text{Fe}^{3+},\text{Mn}^{3+})_2\text{O}_4$

Some of the sharp octahedral grains in the augite skarn may be franklinite, but franklinite was not identified with certainty in the vicinity of the rhodonite skarn. Franklinite, commonly intergrown with gahnite, is found in skarn east of the lens.

Gahnite ZnAl_2O_4

Gahnite, the zinc spinel, is locally common in the area, as in the coarse-grained marble that forms the east wall of the trench, where it occurs as embedded, dark greenish black, euhedral crystals 2.5 to 5 cm across (Fig. 7). It occurs widely in the augite skarn as sharp, greenish black octahedral crystals to 6 mm. Gahnite may be closely associated with augite but is especially prominent in augite-poor patches of calcite, where dozens of small, sharp crystals may be scattered through a hand specimen (Fig 8).



Figure 7. Gahnite (green) and augite in bluish gray calcite (18 cm). University of Delaware specimen, Sharon Fitzgerald photo.



Figure 8. Green gahnite octahedra and ripe-olive augite in bluish gray calcite (11 cm). University of Delaware specimen, Sharon Fitzgerald photo.



Figure 9. Galena in augite – white calcite rock with minor rhodonite (10 cm). Earl Verbeek photo.

Galena PbS

Galena is widespread but sparse at both Franklin and Sterling Hill (Dunn, 1995). In the trench, galena is much more abundant in the rhodonite skarn than in the augite skarn. In the augite skarn, galena commonly infiltrates augite, rendering it dark gray to black. In the rhodonite skarn, galena locally forms nearly pure masses as much as 2.5 cm across, exhibiting high luster and prominent cleavage (Fig. 9). In some specimens the galena is accompanied by another dark, dull black, blue-tarnished mineral (possibly chalcocite), and rarely by small masses of honey-brown sphalerite. Some galena may be part of the rhodonite assemblage; however, the following five lines of evidence suggest that much galena is later. (1) In some specimens galena includes small, sharply angular cleavage fragments of rhodonite, or fragments of quartz. (2) Galena infiltrates and appears to replace at least two of the minerals of the rhodonite skarn: actinolite and rhodonite. Where it replaces actinolite the product is black but retains relict cleavages. (3) Films of fine-grained galena have been observed along cleavage surfaces and hairline fractures in calcite and albite. (4) Galena locally includes crystals and grains of other minerals such as apatite, rhodonite, and genthelvite. Genthelvite crystals embedded in galena range from well-formed tetrahedrons to rounded, apparently partially resorbed crystals

with curiously ribbed surfaces. (5) Galena commonly forms along grain-boundary contacts between actinolite and calcite and may be later than both of these. In some specimens it forms threadlike masses along grain boundaries of those minerals. Similarly, galena in one specimen is in contact with willemite, rhodonite and calcite but is “molded” against their grain boundaries. Galena is easily deformed and recrystallized, so conclusions based on textural evidence are tentative. Some galena is associated with crumbly, altered calcite and is clearly of late origin.

Garnet $(\text{Mn,Ca,Fe})_3^{2+}(\text{Al,Fe})_2(\text{Si}_4\text{O}_3)_3$

Orange garnet, most likely spessartine dominant (Dunn, 1995, p. 360-363), occurs sparingly as masses up to 5 cm in augite skarn, typically associated with biotite. A euhedral crystal about 6 mm was noted in one specimen, associated with augite and sphalerite in bluish gray calcite.

Genthelvite $\text{Zn}_8\text{Si}_6\text{Be}_6\text{O}_{24}\text{S}_2$

Genthelvite (Figs. 10, 11), the mineral of most collector interest in this area, was discussed in some detail by Cianciulli and Verbeek (2003). The genthelvite fluoresces a bright green, paler than willemite, in longwave (365-370 nm) ultraviolet light, and responds more weakly in midrange (300-305 nm) and shortwave (254 nm) light. It is exclusively a mineral of the rhodonite skarn or later assemblages. In the rhodonite skarn, genthelvite, in sharp euhedral crystals to irregular masses may be in contact with rhodonite, actinolite, quartz, willemite, calcite or galena. The largest and best-formed crystals occur embedded in calcite, where some of them measure 7.5 to 8 cm on edge, but where these abut other minerals their faces are ragged and irregular. Pale green, irregular masses of genthelvite measuring 2.5 to 5 cm long are known from a number of specimens in this assemblage.

Genthelvite commonly occurs in grains wholly embedded in other minerals besides calcite. Tiny grains of genthelvite are common in massive quartz, where some of them are best revealed by their green fluorescence. Numerous specimens contain scattered grains and crystals of genthelvite embedded in massive white albite. Some of the crystals are perfectly euhedral; most of these are tiny but a few reach 2.1 cm on edge. Where genthelvite is present in small grains, the visual contrast between it and albite is nearly zero, and the presence of the genthelvite is best determined by examination under longwave ultraviolet light. In several specimens genthelvite occurs as small grains with calcite and willemite in healed fractures through the albite and is thus later. Still other genthelvite grains occur embedded in galena and have been worked out into relief by collectors. The crystals are generally small, 6 to 11 mm on edge, and some are conspicuously rounded.

Genthelvite is also a local component of the rhodonite-calcite-willemite veins cutting through the augite skarn. Associated species in the veins include scheelite, actinolite and galena. Genthelvite appears in some of these veins as sharp euhedra, but the veins are thin and the genthelvite crystals small: most are 0.5 to 2 mm across, and the largest seen thus far is 5 mm. The crystals are embedded in vein calcite and in willemite. Other genthelvite grains in these veins are more irregular, but nonetheless equant.

Finally, genthelvite also occurs within small veinlets cutting massive albite. Some of these veinlets contain thin films of red-fluorescing calcite, but others are empty except for the genthelvite. Under longwave ultraviolet light, linear chains of tiny genthelvite grains reveal the presence of the healed fractures within which they formed.



Figure 10. Genthelvite, white light, 6 cm: genthelvite, calcite, willemite, quartz, minor rhodonite, apatite. This specimen is shown under ultraviolet light in figure 11. MB404 Earl Verbeek photo.

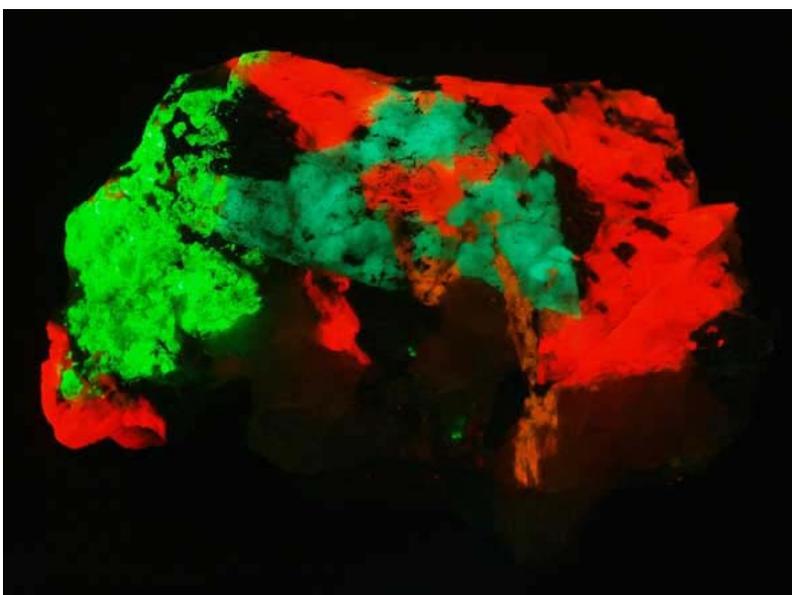


Figure 11. Genthelvite, combined long and short wave UV: genthelvite (bluish green), willemite (bright green), calcite (red), apatite (red-orange). Earl Verbeek photo.

■ **Goethite** $\alpha\text{-Fe}^{3+}\text{O(OH)}$

Goethite, as a weathering product of iron-bearing minerals, is widely distributed at Sterling Hill and locally constituted an important part of the fragmental fill of the Passaic and Noble pits as they were being excavated for hemimorphite during the latter half of the 19th century. In the trench goethite is conspicuous mostly as a pigmenting agent in the fragmental fill, and as “iron stains” on weathered specimens excavated from that fill. In some specimens, however, it occurs in small masses as a weathering product of augite.

■ **Malachite** $\text{Cu}^{2+}_2(\text{CO}_3)(\text{OH})_2$

Malachite is uncommon to rare in this assemblage but occurs locally as a late-stage alteration product of chalcocite. (For further details see under azurite.)

■ **Orthoclase** KAlSi_3O_8

In one specimen a 1.5-cm crystal of alkali feldspar, optically orthoclase perthite, is associated with augite in bluish gray calcite.

■ **Quartz** SiO_2

Quartz, a mineral uncommon to most parts of Sterling Hill, is abundant in the rhodonite skarn in the genthelvite trench as irregular grains and masses to 2.5 cm. The quartz is milky, translucent to nearly transparent in places. Rhodonite, altered bustamite, and calcite are almost always present in association (Figure 16). Quartz locally encloses grains of other minerals, notably genthelvite, willemite, and rarely apatite. Two specimens show quartz enclosing broken rock fragments from the augite skarn.

■ **Rhodonite** $\text{Ca}(\text{Mn,Zn})_4\text{Si}_5\text{O}_{15}$

Rhodonite has three occurrences: (1) as brownish pink, irregular masses to at least 5 cm, enclosing spheroidal grains of bluish gray calcite in poikiloblastic texture and associated with equant augite in bluish gray calcite (Fig. 12); (2) as large single-crystal grains as much as 7.5 cm across enclosing altered bustamite and associated with bladed augite and quartz (Figure 13); and (3) as brighter pink blades up to 2.5 cm in white calcite associated with actinolite and commonly enclosing small oriented flakes of actinolite (Fig. 4, 14). As noted above, actinolite may occur as rings of small, oriented flakes toward the outside of large grains of rhodonite of the second occurrence. The textural relationships between actinolite and rhodonite are complex, but suggest that much rhodonite grew before crystallization of actinolite began, that rhodonite continued to form when actinolite was crystallizing, and that in some cases one replaced the other (see above under actinolite).



Figure 12. Rhodonite (7 cm): rhodonite single crystal including bluish gray calcite in poikiloblastic texture. University of Delaware specimen, Sharon Fitzgerald photo.



Figure 13. Rhodonite (12 cm): rhodonite single crystal with augite, albite. Jeff Glover photo.



Figure 14. Rhodonite (14 cm): Rhodonite crystal with augite, genthelvite (pale green wedge to right of rhodonite), quartz, white calcite. SHMM-195 Jeff Glover photo.

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Scheelite CaWO_4

A mineral of the scheelite-powellite series has been tentatively identified, based on fluorescence and the presence of both minerals elsewhere at Sterling Hill; no specimens have been analyzed thus far. It occurs as inconspicuous, sparse, glassy grains, greenish honey-colored to mustard-yellow, from pinpoint size to 2 mm. In three specimens the scheelite is in thin rhodonite veins cutting through augite skarn; these veins also contain genthelvite, galena, calcite, and actinolite. In other specimens scheelite appears to be a later mineral. The fluorescence ranges from bright pale yellow to bright yellowish white in shortwave ultraviolet light, and even a little brighter in midrange ultraviolet light. The bright yellowish white fluorescence is more suggestive of molybdenum-rich scheelite than of powellite.

Sphalerite ZnS

Sphalerite appears to be of two distinct generations. It occurs sparsely as anhedral, pale yellow grains to 3 mm across, showing prominent cleavage, in augite skarn that shows no visible signs of alteration (Fig. 2). This sphalerite is easily identified by its pale sky-blue fluorescence in longwave ultraviolet light. Blue-fluorescent sphalerite in small grains is known from elsewhere at Sterling Hill and Franklin, particularly in the “black willemite ore” zone at Sterling Hill and in similar dark-colored willemite-franklinite ore from Franklin. Davis (1993) has shown that most pale (“cleiophane”) sphalerite at Sterling Hill is a high-temperature mineral of the ore. Sphalerite has also been found as honey-colored anhedral masses, the largest about 1 cm across, showing prominent cleavage and bright orange longwave fluorescence, with galena and chalcocite. This orange fluorescence is characteristic of late sphalerite at Sterling Hill.

Titanite CaTiOSiO_4

Titanite is fairly common as tiny, root-beer-brown, euhedral crystals showing characteristic diamond-shaped profiles, embedded in actinolite, calcite, genthelvite or rhodonite in the rhodonite skarn (Fig. 15). Additional titanite crystals occur along grain boundaries between all of these minerals. In some specimens titanite is locally abundant, but almost always in small grains; however, the largest crystal noted, embedded in white calcite, is about 2.5 cm long.



Figure 15. Titanite (12 cm): diamond-shaped 2-cm titanite crystal in white calcite with actinolite. University of Delaware specimen, Sharon Fitzgerald photo.

Titanite commonly contains minor uranium and can be used for radiometric dating; samples were sent for this purpose to Dr. George Gehrels at the University of Arizona. However, the samples contained about 600 ppm nonradiogenic (ordinary) lead and only about 30 ppm uranium. Only a few ppm radiogenic lead would have been produced by the breakdown of uranium, and it could not be resolved from the much more abundant ordinary lead, so an age determination was not possible.



Figure 16. Transitional assemblage: dull orange altered bustamite (top center) surrounded by a single crystal of rhodonite, with prismatic augite, quartz, and green prisms of apatite (15 cm). University of Delaware specimen, Sharon Fitzgerald photo.

Willemite Zn_2SiO_4

Willemite is a widely distributed mineral of the rhodonite skarn, but in most specimens it is either visually inconspicuous or is easily mistaken for other minerals; it is best recognized by its bright green fluorescence in shortwave ultraviolet light (Fig. 11). Willemite occurs as anhedral grains, commonly of a mottled color, generally measuring 5 to 20 mm but in rare cases up to 10 cm. Most such willemite is glassy and reddish brown to brownish purple or maroon in color, but some is gray, brownish white, or orange-tan. Where present in large grains, the willemite commonly contains abundant and visually prominent rod-like oriented inclusions, not yet studied. Occasionally it includes small grains of other minerals such as actinolite, apatite or genthelvite. In color and habit this willemite is wholly unlike that of the normal Sterling Hill ore.

Willemite is also prevalent within veins cutting the augite-calcite skarn. Many such veins are thin, 1 cm

or less, with rhodonite, calcite, willemite, and genthelvite as common constituents.

Willemite is very common as thin, patchy coatings within tiny hairline fractures in quartz, rhodonite, albite and calcite. Most such fractures have developed along cleavage planes, giving rise to multiple parallel veinlets.

Zircon $ZrSiO_4$

Zircon is widely distributed at Franklin and Sterling Hill, but owing to its generally small crystal size and volumetric insignificance it is often overlooked. Only two zircon crystals were noted in the trench, one embedded in coarse-grained calcite and associated with augite, actinolite, albite and genthelvite in a highly weathered specimen, and the other a euhedral brown crystal, about 1 cm, embedded in white calcite and associated with rhodonite and coarse actinolite. A fragment from the margin of this crystal was sent to George Gehrels' radiometric dating laboratory at the University of Arizona, and yielded a date of 1029 Ma. The methodology of obtaining this date, and the significance of the date, are discussed below

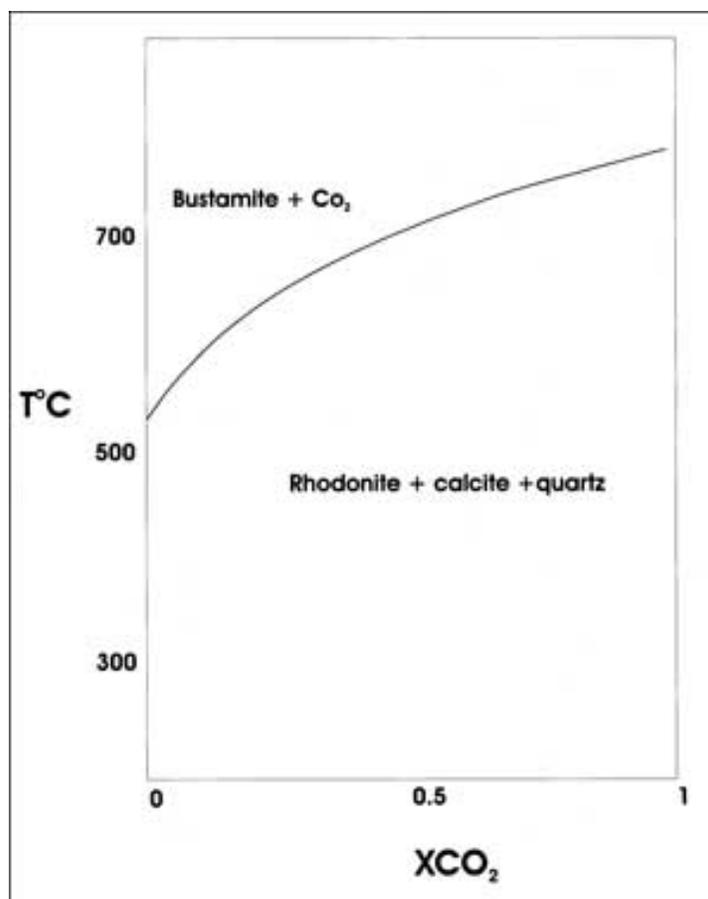


Figure 17. Schematic T - XCO₂ phase diagram showing the stability fields of bustamite + CO₂ and of rhodonite + calcite + quartz, as a function of temperature in degrees Celsius (T) and molecular fraction of CO₂ (XCO₂) in a pore fluid of carbon dioxide and water at a total pressure of about 5 kb. The shape of the curve separating the fields is based on the calculated curve for the reaction Calcite + CO₂ = Wollastonite in Duzs-Moore et al. (2003), but its position is an estimate.

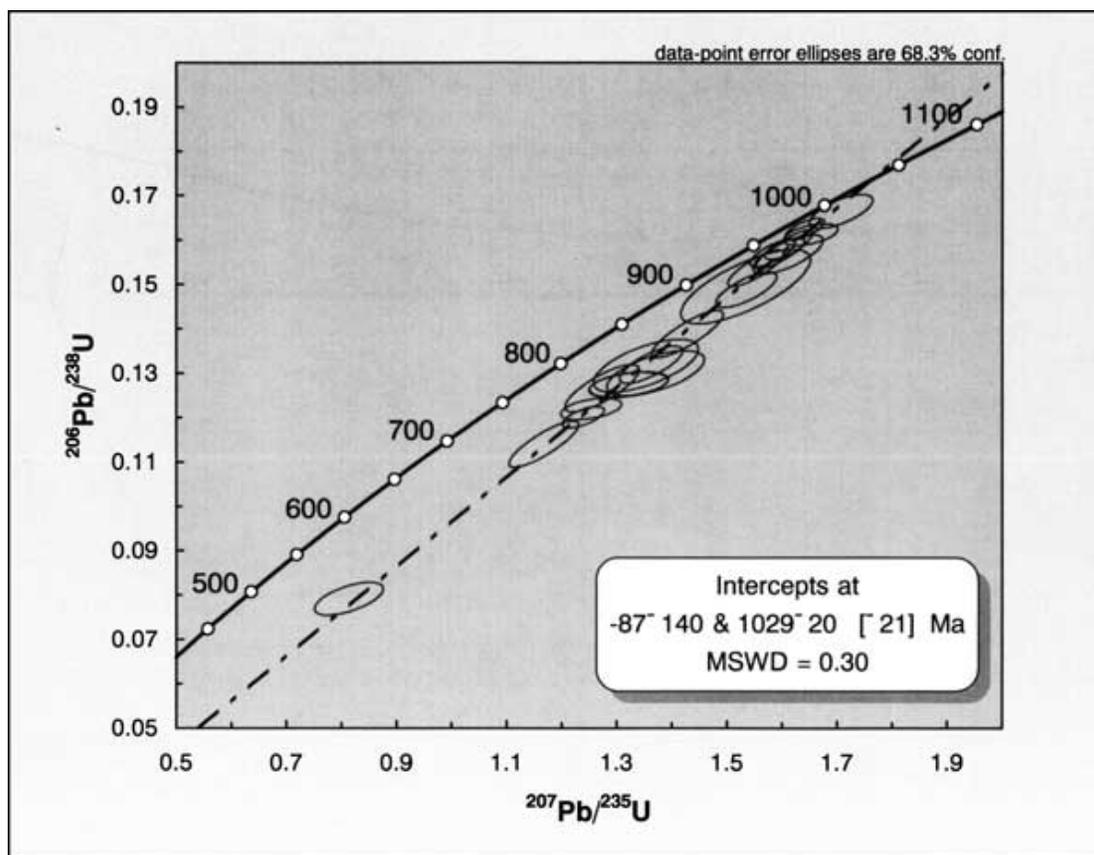


Figure 18. Concordia/discordia diagram of U/Pb dates for the zircon crystal from the trench.

ASSEMBLAGES

A metamorphic mineral assemblage is a set of minerals which are found together and which appear to have formed together under a particular temperature and pressure regime. There appear to be three metamorphic mineral assemblages as uncovered in the trench; these are listed in Table II. First is the augite skarn assemblage, typical of the Pyroxene Zone, containing bluish gray calcite (Fig. 2, 7, 8, 12.) Next is a transitional assemblage containing bustamite, rhodonite, quartz, calcite and augite (Fig. 6, 16). Finally there is the rhodonite skarn assemblage containing rhodonite, actinolite, albite, titanite, willemite, and genthelvite (Fig. 3, 4, 10, 11, 14, 15). Throughout the Sterling Hill deposit, different mineral assemblages in the skarn and ores show sharp boundaries, indicating that in most cases there was not a great deal of diffusion of different elements, and that metamorphic reactions involved relatively small volumes of rock.

There are also later, apparently hydrothermal minerals, including galena, chalcocite and scheelite, and finally weathering minerals, including azurite, malachite and goethite.

Table II: Metamorphic minerals in the Trench.

Augite skarn

augite (equant)
biotite
bustamite
calcite (pale bluish gray)
gahnite
rhodonite
spessartine
sphalerite

Transitional assemblage

augite (prismatic)
bustamite
calcite (white)
quartz
rhodonite

Rhodonite skarn

actinolite
albite
calcite (white)
galena
genthelvite
quartz
rhodonite
titanite
willemite

DISCUSSION

Much of the augite skarn is composed almost entirely of augite and calcite, with some gahnite, minor sphalerite, garnet, and biotite. In addition to the usual Ca, Mg and Fe, augite from Sterling Hill contains almost as much Mn as Fe, significant Zn and Na, and minor Al. This chemical complexity is compatible with a high temperature of formation, as the ability of minerals to accept a wide range of elemental substitutions increases with temperature. In metamorphic rocks, augite is characteristic of the highest temperatures of metamorphism, and we can conclude that the augite skarn formed at the peak of metamorphism at Sterling Hill, at about 750° C.

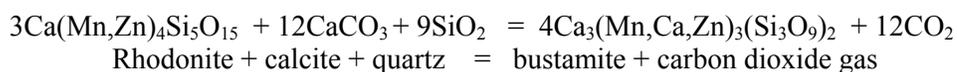
Actinolite, however, is unstable relative to hornblende or augite at high metamorphic temperatures. It is characteristic of metamorphic rocks formed at much lower temperatures, typically 350° to 450° C. Tremolite, the iron-free version of actinolite, occurs in the Franklin Marble only because of its high fluorine content, which stabilizes it against the dehydration reactions by which it breaks down at high temperature. Since the

■
■
actinolite of the rhodonite skarn has essentially no F, the only way to explain its presence is to assume that it formed at a temperature lower than that which existed during the peak of metamorphism, as a later, retrograde mineral.

Table III gives analyses of some minerals from Sterling Hill and Franklin. Semiquantitative EDS analyses of some of the trench minerals are compatible with the analyses shown. We can do a rough chemical comparison showing how the elements in the augite skarn could be reconstituted into the minerals of the rhodonite skarn. Most of the elements in the augite could have gone to form actinolite, with minor Na and Ti for albite and titanite. Since actinolite can accept both magnesium and iron, the total of the two in the analysis is more significant than the individual amounts. Since there is more calcite proportionally in the rhodonite skarn than in the augite skarn, the excess calcium in the augite and the bustamite could have gone to form some of the extra calcite in the rhodonite skarn. Overall the augite skarn and the rhodonite skarn are very similar in bulk composition. This similarity is compatible with the hypothesis that the rhodonite skarn formed by retrograde metamorphism of the augite skarn.

The presence of bustamite provides further information. Bustamite is a high-temperature mineral common at Franklin, where it typically occurs as crystals in calcite, at the edges of feldspathic bodies. At Sterling Hill it has been found only in the genthelvite trench and at one other occurrence (Duzs-Moore et al., 2003), where it forms isolated, bright pink grains in calcite, with small wollastonite grains rimming the bustamite grains.

Bustamite could form by the reaction



This is a prograde reaction; that is, bustamite is stable at higher temperatures than the other combination of minerals and forms from them as temperature increases during metamorphism. Since the reaction releases CO₂, the temperature at which the reaction takes place depends on the proportion of CO₂ (XCO₂) relative to other components, mostly H₂O, in the pore fluid, as indicated in Figure 15; the higher the XCO₂, the higher the temperature needed for bustamite to form. Most of the bustamite found in the trench is dull, with an altered appearance, and is surrounded by rhodonite and quartz; in fact, quartz is found almost exclusively in proximity to altered bustamite, and rhodonite is most abundant as rims around altered bustamite grains. These features suggest that the reaction given above was running backwards and that the bustamite was being consumed to form rhodonite + calcite + quartz. Such a reaction would be retrograde, occurring as temperature fell or XCO₂ rose (or both) after the peak of metamorphism, but must have begun at sufficiently high temperature that augite was still stable. Most of the rhodonite and all of the quartz could have formed from the alteration of bustamite, which would supply the extra manganese needed, and which would also contribute to the higher proportion of calcite in the rhodonite skarn. Under the electron microscope, the most heavily altered bustamite grains can be resolved into a fine-grained mixture of bustamite, rhodonite, calcite and quartz, a texture that suggests that there may have been two stages of bustamite alteration: an earlier one during which the large rhodonite grains grew around bustamite, and a later one during which remaining bustamite was altered to the fine-grained mixture. In the absence of extra quartz or other sources of silica, rhodonite is stable over a wide range of conditions from low-grade to very high-grade metamorphism. This wide stability range accounts for the occurrence of rhodonite with (a) augite and bluish gray calcite in the augite skarn, (b) as an alteration of bustamite in the transitional assemblage, and (c) with actinolite in the rhodonite skarn.

Table III: Analyses of Sterling Hill/Franklin Minerals, from the literature

| | Augite | Actinolite | Rhodonite | Bustamite |
|--------------------------------|--------|------------|-----------|-----------|
| SiO ₂ | 50.0 | 53.0 | 47.9 | 46.72 |
| Al ₂ O ₃ | 2.9 | 1 | | 1.34 |
| MgO | 8.4 | 14 | 1.7 | 1.27 |
| CaO | 19.6 | 10 | 7.7 | 22.24 |
| MnO | 5.6 | 5 | 32.7 | 26.51 |
| FeO | 8.8 | 5 | 5.2 | 0.46 |
| ZnO | 2.4 | 9 | 6.5 | 1.34 |
| Na ₂ O | 1.4 | 1 | | |

References:

Augite: C2410, Sterling Hill, Dunn, 1995

Actinolite: R18242, Franklin, Dunn, 1995

Rhodonite: R19116, Sterling Hill, Dunn, 1995

Bustamite: Franklin, Palache, 1935

Based on these different assemblages, we tentatively suggest a complex history for the rocks of the trench. The augite skarn formed at the peak of metamorphism and originally contained minor bustamite. At some time near the end of the metamorphic episode, at temperatures at which augite was still stable but bustamite was not, water-bearing CO₂-rich fluid permeated the rock locally. In the absence of such fluids, the minerals formed at high temperatures of metamorphism would have been preserved. The bustamite began to alter to rhodonite + quartz + calcite, and the large single crystals of rhodonite grew, surrounding the bustamite. Some augite formed or recrystallized as bladed grains. Much later, at still lower temperature, another pulse of fluid invaded the rock and catalyzed the growth of actinolite and of rhodonite with actinolite inclusions. The actinolite-bearing rims grew on the large rhodonite grains surrounding bustamite at this time, and most of the remaining bustamite altered to the fine-grained mixture of rhodonite, calcite and quartz.

The presence of Zn and Mn makes it difficult to be certain of the temperature of formation of the rhodonite skarn; these elements would tend to extend the stability ranges of the minerals that incorporate them as minor elements. However, all the amphiboles and pyroxenes can contain Mn and Zn, whereas feldspars do not accept either of them. Therefore, the influence of these elements in changing the stability ranges of the augite, actinolite, rhodonite and bustamite relative to each other is likely to be minor. If we ignore the possible influence of Zn and Mn, the mineral assemblage of actinolite + albite + calcite + quartz + titanite is typical of upper greenschist facies metamorphism, which is stable over a temperature range of roughly 350° to 450° C, depending on pressure and total rock composition. Because the augite skarn and the rhodonite skarn are chemically quite similar, we can conclude that the rhodonite skarn formed by retrograde metamorphism of augite skarn.

Genthelvite, the mineral of greatest interest to collectors of fluorescent minerals, appears to have formed initially during crystallization of the rhodonite-actinolite retrograde assemblage. However, like willemite at Franklin/Sterling Hill, genthelvite appears to have remobilized readily, as it also occurs in healed fractures in albite and as euhedral crystals with galena.

DATING THE ASSEMBLAGES

The zircon grain mentioned above gave a radiometric date of 1029 ± 20 Ma (million years ago), placing it near the end of high-temperature metamorphism in the New Jersey Highlands, and similar to the date that has been established (1020 Ma) for the intrusion of the undeformed Mt. Eve granite in Orange County, New York, at the northern end of the Franklin Marble.

A complete discussion of the complex theory behind radiometric age determinations (summarized here) is given in a number of textbooks, such as Faure (1977). Zircon commonly contains small amounts of U substituting for Zr in its atomic structure. Radiometric dating of zircon is based on the radioactive decay of U^{238} to Pb^{206} and of U^{235} to Pb^{207} . Since the two isotopes of uranium break down at different rates to different isotopes of lead, they provide independent measurements of the date. For any age, there will be definite values of Pb^{206}/U^{238} and Pb^{207}/U^{235} ; these ratios define a line called the *concordia*, and any point on the concordia corresponds to a definite age. The concordia diagram is useful, because if a zircon (or other mineral being dated) has lost lead during its history, the isotopic ratios of Pb and U will not fall on the concordia, but the date can still be determined if isotopic *ratios* have not changed – if both isotopes were lost at the same rate. If a number of zircon grains or a number of points on a single grain are dated using both U^{238} and U^{235} , the Pb/U ratios will tend to fall on a straight line, called a *discordia*. The discordia will intersect the concordia at two points, corresponding to two ages. The older date is the actual date of formation of the zircon. The younger date depends on whether the zircon lost lead during a specific episode or gradually over time.

Figure 16 is a concordia diagram for the Sterling Hill zircon, and Table IV gives the data on which it is based. The solid line is the concordia, with ages in Ma indicated on it. The dashed line is the discordia for the Sterling Hill zircon; the ellipses on the discordia are individual Pb and U measurements, with the size of the ellipse indicating the uncertainty of the measurement, measured at 2-sigma, the 95% confidence level. The discordia intercepts the concordia at 1029 ± 20 Ma (the age of the zircon) and at -87 ± 140 Ma (in the future). If the zircon lost lead gradually, during the slow cooling of the New Jersey Highlands after metamorphism, such a meaningless date as the lower intercept may arise, and we believe this interpretation is most likely.

So what are the possible dates for the formation of the retrograde assemblages? Carvalho and Sclar (1988) noted that different minerals from the New York-New Jersey Highlands give different radiometric dates. Argon (Ar) ages of hornblende average 919 Ma (Volkert, 2005), and those of biotite average 790 Ma. Ar can escape from hornblende at temperatures above 500°C and from biotite above 325°C , so these dates indicate not when these minerals formed, but the time when temperatures had fallen low enough that the minerals became sealed against Ar loss (their “closure temperatures,” when lattice contraction had proceeded far enough to prevent escape of Ar from the mineral grains). Based on these dates and temperatures, the New Jersey Highlands cooled 175°C in 129 million years, for an average of 1.36°C per million years. If we project this rate of cooling back in time, the rocks of the region would have been at a temperature of about 650°C at 1029 Ma, and 750°C at about 1100 Ma, during the early part of the Ottawan Orogeny, when there was extensive igneous intrusive activity in the New Jersey Highlands. (The peak temperature most likely actually occurred somewhat later in the Ottawan Orogeny.) The 1029 Ma date on the zircon crystal is close to the date (1020 Ma) for the intrusion of the undeformed Mt. Eve granite in Orange County, New York, at the northern end of the Franklin Marble. Since the granite is undeformed, it was intruded after significant deformation in the region had ceased, but while temperatures were still high. The intrusion of the Mount Eve granite could have been accompanied by minor regional hydrothermal activity, and the zircon date of 1029 Ma may give the time of formation of the transitional assemblage of rhodonite+quartz + augite at about 650°C ; augite would be stable at this temperature. This conclusion is tentative, as the zircon grain was associated with actinolite and rhodonite, but we feel the indicated date is too old and suggests a temperature too high for the zircon to have formed along with the rhodonite skarn assemblage. If 450°C is the upper limit of the

temperature for the rhodonite-actinolite skarn, it could have started forming at about 880 Ma and could have continued forming until as late as 810 Ma at around 350°C during continued cooling of the region following the Ottowan Orogeny. Interestingly, there is a lot of evidence for at least one major retrograde event in the Franklin Marble and the Sterling Hill and Franklin orebodies. Besides this occurrence, there are the garnet rims on franklinite from Franklin, margarite-gahnite associations from the nearby Limecrest quarry observed by PBL, and wollastonite altered to the retrograde assemblage calcite + quartz found in the old classic vesuvianite locality at Amity, New York (Altounian, 2001). Are they all the same? They all appear to be greenschist facies assemblages, but whether they are contemporaneous or not could only be determined from radiometric dating.

Table IV. U-Th-Pb geochronologic data.

| | | | | | Isotopic ratios | | | | | | Apparent ages (Ma) | | | |
|----------|-------|-------------------|------|--------------------|-----------------|--------------------|-----|-------|--------------------|------|--------------------|------|--------------------|------|
| Analysis | U | ²⁰⁶ Pb | U/Th | ²⁰⁷ Pb* | ± | ²⁰⁶ Pb* | ± | error | ²⁰⁶ Pb* | ± | ²⁰⁷ Pb* | ± | ²⁰⁶ Pb* | ± |
| | (ppm) | ²⁰⁴ Pb | | ²³⁵ U | (%) | ²³⁸ U | (%) | corr. | ²³⁸ U | (Ma) | ²³⁵ U | (Ma) | ²⁰⁷ Pb* | (Ma) |
| 1 | 2350 | 941 | 31.0 | 1.65203 | 2.0 | 0.16125 | 1.0 | 0.51 | 963.7 | 9.0 | 990.3 | 12.5 | 1049.7 | 34.4 |
| 2 | 2201 | 1582 | 30.4 | 1.64100 | 1.4 | 0.16244 | 1.0 | 0.70 | 970.3 | 9.1 | 986.1 | 9.1 | 1021.4 | 20.8 |
| 3 | 2387 | 365 | 30.3 | 1.16756 | 3.6 | 0.11404 | 3.0 | 0.85 | 696.1 | 20.0 | 785.5 | 19.5 | 1048.4 | 38.4 |
| 4 | 2008 | 423 | 32.2 | 1.53517 | 2.4 | 0.14877 | 1.8 | 0.75 | 894.1 | 14.8 | 944.6 | 14.6 | 1064.1 | 31.8 |
| 5 | 1919 | 794 | 27.7 | 1.53394 | 5.1 | 0.14951 | 3.7 | 0.73 | 898.2 | 31.0 | 944.1 | 31.2 | 1052.7 | 69.9 |
| 6 | 2536 | 667 | 30.5 | 1.27366 | 3.5 | 0.12662 | 2.8 | 0.79 | 768.5 | 20.1 | 834.0 | 19.9 | 1012.7 | 43.1 |
| 7 | 2205 | 846 | 28.9 | 1.61105 | 2.6 | 0.15681 | 1.9 | 0.72 | 939.0 | 16.3 | 974.5 | 16.3 | 1055.4 | 36.7 |
| 8 | 2597 | 1089 | 31.6 | 1.60481 | 1.5 | 0.15806 | 1.0 | 0.67 | 946.0 | 8.8 | 972.1 | 9.4 | 1031.5 | 22.5 |
| 9 | 2648 | 500 | 32.7 | 1.32113 | 3.6 | 0.12740 | 1.5 | 0.41 | 773.0 | 10.8 | 855.0 | 20.8 | 1074.2 | 65.8 |
| 9 | 2648 | 500 | 32.7 | 1.32241 | 3.6 | 0.12752 | 1.5 | 0.41 | 773.7 | 10.8 | 855.6 | 20.8 | 1074.2 | 65.8 |
| 10 | 2295 | 478 | 29.1 | 1.25368 | 2.9 | 0.12198 | 1.3 | 0.45 | 741.9 | 9.3 | 825.1 | 16.5 | 1056.2 | 52.4 |
| 11 | 2433 | 1099 | 31.2 | 1.60415 | 2.1 | 0.15789 | 1.8 | 0.86 | 945.0 | 16.1 | 971.8 | 13.3 | 1032.9 | 22.1 |
| 12 | 2021 | 224 | 34.1 | 1.35313 | 4.7 | 0.13170 | 3.0 | 0.64 | 797.5 | 22.3 | 868.9 | 27.2 | 1055.5 | 72.2 |
| 13 | 2050 | 1301 | 29.4 | 1.58257 | 1.7 | 0.15703 | 1.3 | 0.76 | 940.2 | 11.3 | 963.4 | 10.6 | 1016.6 | 22.7 |
| 14 | 2148 | 432 | 30.5 | 1.23928 | 2.0 | 0.12011 | 1.3 | 0.65 | 731.2 | 9.2 | 818.6 | 11.4 | 1064.0 | 30.7 |
| 15 | 2104 | 251 | 29.4 | 0.81358 | 5.1 | 0.07916 | 3.1 | 0.61 | 491.1 | 14.6 | 604.5 | 23.1 | 1056.2 | 80.8 |
| 16 | 1961 | 951 | 33.8 | 1.55242 | 2.1 | 0.15369 | 1.8 | 0.83 | 921.6 | 15.2 | 951.5 | 13.3 | 1021.2 | 24.5 |
| 17 | 2235 | 215 | 27.7 | 1.37063 | 4.3 | 0.13003 | 2.6 | 0.60 | 788.0 | 19.1 | 876.4 | 25.0 | 1106.8 | 67.8 |
| 18 | 2406 | 501 | 32.7 | 1.42864 | 3.0 | 0.13883 | 2.5 | 0.84 | 838.1 | 19.8 | 901.0 | 17.9 | 1058.6 | 32.6 |
| 19 | 2259 | 481 | 25.2 | 1.36244 | 2.8 | 0.13195 | 2.1 | 0.76 | 799.0 | 15.7 | 872.9 | 16.2 | 1065.5 | 36.2 |
| 20 | 2018 | 1181 | 31.3 | 1.70733 | 2.2 | 0.16647 | 1.5 | 0.68 | 992.6 | 14.0 | 1011.3 | 14.4 | 1051.9 | 33.1 |

Notes:

1. Uncertainties for individual analyses are reported at the 1-sigma level, and include only measurement errors.
2. Analyses conducted by LA-MC-ICPMS, as described by Gehrels et al. (2008).

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3. U concentration and U/Th are calibrated relative to Sri Lanka zircon standard, and are accurate to ~20%.
 4. Common Pb correction is from measured ^{204}Pb .
 5. Common Pb composition interpreted from Stacey and Kramers (1975).
 6. Common Pb composition assigned uncertainties of 1.0 for $^{206}\text{Pb}/^{204}\text{Pb}$, 0.3 for $^{207}\text{Pb}/^{204}\text{Pb}$, and 2.0 for $^{208}\text{Pb}/^{204}\text{Pb}$.
 7. U/Pb and $^{206}\text{Pb}/^{207}\text{Pb}$ fractionation is calibrated relative to fragments of a large Sri Lanka zircon of 563.5 ± 3.2 Ma (2-sigma).
 8. U decay constants and composition as follows: $^{238}\text{U} = 9.8485 \times 10^{-10}$, $^{235}\text{U} = 1.55125 \times 10^{-10}$, $^{238}\text{U}/^{235}\text{U} = 137.88$.
 9. Concordia diagram created with Ludwig (2003).

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