Ferroaxinite was first discovered at the Lime Crest quarry, Sparta, New Jersey, in 1993. Over the next two years a small number of specimens containing vugs with free-standing crystals were collected. The ferroaxinites were all found in a hydrothermal vein within a small granite body exposed in the quarry; none were found in the adjacent Franklin Marble. All the material apparently came from a single axinite-quartz-calcite vein, fragments of which were exposed on the sides of large, stockpiled boulders. In the specimen examined for this study the vein contained a $4 \times 1 \times 1$-cm lenticular cavity lined with quartz, ferroaxinite, and calcite crystals. Here we report results of the mineralogical and petrological analyses of this specimen. The results are discussed in the context of other axinite-group mineral locations in the Reading Prong Highlands.

Geology

The Lime Crest quarry is situated at the northwestern edge of the Reading Prong Highlands in Sussex County, New Jersey. The Reading Prong is underlain by Proterozoic-age metamorphic rocks and stretches from western-most Connecticut to near Reading, Pennsylvania; it is one of a series of Precambrian highlands that form the metamorphic/igneous core of the
north-central Appalachians (fig. 3). The rocks of this region have been studied for more than 150 years, some portions of them intensely. This interest was first driven by the widespread occurrence of iron ore, exploited from colonial times until the 1960s, and the presence of the large, unique zinc deposits at Franklin and Sterling Hill, New Jersey.

The Reading Prong massif is a major Precambrian complex, one of several outcropping between the sedimentary rocks of the Appalachian basin and the Paleozoic metamorphic terrains of New England and the southeastern Piedmont. Metamorphism of the Reading Prong rocks occurred during the Grenville Orogeny, approximately 1.15 billion years ago, and reached the hornblende granulite facies in the Lime Crest region. Metamorphic recrystallization and deformation have been so severe that nearly all of the original sedimentary and volcanic features of the rocks have been erased and the relationships between lithologic units have been distorted. The Franklin Marble was the least competent lithology and suffered the most intense deformation. The Lime Crest quarry, because of its proximity to the Cork Hill Gneiss, is one of the few localities where one can discern a stratigraphy within the marble. The Precambrian complex has been interpreted by Volkert and Drake (1999) as a continental, Andean-type, magmatic arc overlain by sediments and volcanics. These pre-Grenville lithologies were extensively intruded by synorogenic granites during the Grenville event.

Subsequently, between the Late Proterozoic and the Mesozoic (Drake 1999), the rocks throughout the region suffered periodic episodes of deformation. Deformation was especially intense during the Late Permian Alleghanian Orogeny when the region was pervasively fractured during the development of imbricated thrust sheets. The thrusting juxtaposed the Precambrian rocks in a structurally high position relative to the thick section of lower Paleozoic rocks immediately to the west. For more comprehensive discussions of this and various other aspects of the geology of the region, the reader is referred to Herman et al. (1997) and Volkert and Drake (1999).

The Lime Crest quarry works an isolated outcrop of Franklin Marble approximately 2 miles southwest of the formation’s main outcrop belt. The marble exposed in the quarry is indistinguishable from that of the main belt. It is white to pale gray, medium to very coarsely crystalline calcite and dolomite, and contains abundant noncarbonate minerals, most
commonly graphite, chondrodite, phlogopite, tremolite, pyrrhotite, and scapolite. The marble also contains a wide variety of minor minerals and mineral assemblages. Among these are small concentrations of boron-rich minerals, most commonly uvite and fluoborate, which are highly localized but occur throughout the marble (Moore 1992). Although these species have been identified at Lime Crest, they occur sparingly. Most noncarbonate minerals occur in discontinuous bands and lenses within the marble.

The marble also contains thin bands and lenses of gneiss, often in boudinage structure. Most of the gneiss is granitic, contains varying amounts of hornblende and calc-silicate minerals, and is commonly rimmed by pyroxene-rich skarn. However, at Lime Crest one prominent band is a black, finely crystalline rock, with no discernible internal structure, that appears to be conformable and provides a good stratigraphic marker.

To the east of the Lime Crest quarry, the metasedimentary Cork Hill Gneiss overlies the marble. The contact between the marble and the gneiss is well exposed, and the gneiss is extensively quarried in the upper benches on the pit’s eastern side.

Just to the west of the quarry a thrust fault lies under glacial cover and dips at a moderate angle beneath the quarry. The depth of the fault beneath the present quarry floor is unknown but exceeds 150 feet (Warren Cummings, per. com., 2002). Precambrian rocks, along with the Early Cambrian Hardyston and Leithsville Formations, are thrust over the Leithsville and onto the Late Cambrian Allentown Formation (Drake and Volkert 1993; Herman et al. 1997).

The metamorphic rocks along the northwest margin of the Reading Prong, as well as the adjacent Paleozoic carbonates, contain epigenetic minerals deposited predominantly in open spaces. Some of these are Mississippi Valley–type lead-zinc assemblages (Cummings 1993) that indicate deposition in an environment where the chemistry was fluid dominated. Others are assemblages of rock-forming minerals and appear to be recrystallization products of the country rock. At few localities, most notably the Buckwheat Dolomite (Cummings 1988), both types occur in the same structure.

Seven occurrences of epigenetic rock-forming mineral assemblages, scattered between Bethlehem, Pennsylvania, and Fishkill, New York, have included axinite-group minerals. All occur in calcium-rich gneisses such as amphibolites and skarns* or in granitic rocks intimately associated with marble and skarn. All are located in close proximity to the Paleozoic sedimentary rocks. Most of these occurrences appear to have been very small, perhaps limited to a single fissure. Most of the older discoveries were poorly documented. Axinite-group minerals occur in the Reading Prong from southwest to northeast at (1) the Camels Hump near Bethlehem, Pennsylvania: manganaxinite in calc-silicate gneiss or skarn associated with minor marble (the earliest find was reported by Frazier in 1882); (2) Bridgeville, New Jersey: ferroaxinite in many veins and gashes in mafic gneiss near its contact with dolomitic marble (Cummings 1983); (3) Lime Crest quarry, Sparta, New Jersey: ferroaxinite (Mn-rich, 4.8 wt. % MnO) in pegmatitic granite engulfed in marble (Cummings 1997; this article); (4) Sterling Hill mine, Ogdensburg, New Jersey: manganaxinite in the gneiss closely associated with the ores and marble (Palache 1935; Dunn 1995); (5) Goosberry Iron mine, Franklin, New Jersey: ferroaxinite in epidote-calciite vein in calc-silicate gneiss near the Franklin–Cork Hill contact (Palache 1935); (6)

---

*For a discussion of skarn, see the Word to the Wise column in this issue.
Franklin, New Jersey, many localities: ferroaxinite (Mn-rich, 4 wt. % MnO) in the footwall gneiss cut by the Palmer shaft near the contact with marble (Dunn 1995; Palache 1935), manganooxinite in the main shaft of the Trotter mine (Palache 1935), and manganooxinite at the Parker shaft (Palache 1935); and (7) Fishkill, New York: axinite in pegmatite associated with skarn and minor marble, shaft 7 of the New York aqueduct tunnel (Zodiac 1941). All of these locations are close to the Paleozoic rocks and are also in proximity to marble.

The compositions of the axinite-group minerals from the various Reading Prong localities show some relationships to the country rocks present in the vicinity of deposition. Those found in very close proximity to marble and/or manganiferous zinc ores, such as the material from Bethlehem, Pennsylvania, and Lime Crest and Sterling Hill, New Jersey, tend to be more manganiferous ferroaxinite or manganooxinite. Examples recovered from sites a bit more removed from marble tend to be more iron-rich. The example from the granite at Lime Crest quarry is very low in magnesium relative to those found in rocks containing more ferromagnesian minerals.

Mineralogy

Dark pink to brown transparent ferroaxinite crystals fill a 4 × 1 × 1-cm lenticular vug within an axinite-quartz calcite vein in the host granite (fig. 2). In most of the vein axinite is the dominant mineral. In the vug the crystals are lustrous and exquisitely euhedral and occur in a simple paragenesis: quartz, then ferroaxinite, and then calcite (figs. 4–7). The ferroaxinite crystals range from 1 to 4 mm and exhibit the “ax-head” habit typical of this mineral group. The most common forms for these crystals, visually identified, are {001}, {111}, {100}, {110}, and {110}. Chemical analysis of the axinite was performed using a Cameca SX–100 electron microprobe at the

New Mexico Bureau of Mines and Mineral Resources, Soccoro, New Mexico. The microprobe was operated at 15 kV and 19.9 nA. Mineral standards were used. Oxide weight percents are: SiO$_2$ = 42.53, Al$_2$O$_3$ = 18.491, MgO = 0.257, CaO = 19.624, MnO = 4.861, FeO = 7.554, H$_2$O = 1.447, and B$_2$O$_3$ = 6.11 (B$_2$O$_3$ wt. % estimated from published values of other axinite analyses); total = 100.89. The recalculated formula (Fe$_{0.55}$Mn$_{0.39}$Mg$_{0.06}$)Ca$_2$Al$_3$BSi$_3$O$_{16}$(OH) indicates that the crystals are manganese-rich ferroaxinite.

Host Rock Petrography

The granite sample hosting the ferroaxinite vein was found as a lone 61 × 45 × 16-cm boulder at the bottom of the quarry. It is massive, white to pale gray, and medium to coarse grained. Larger crystals of feldspar and quartz dominate the host rock (fig. 2). Perthitic textures are found throughout the rock along with myrmekitic textures, an intergrowth of plagioclase feldspar and vermicular quartz. Other minerals, such as chlorite and pyroxene, are found dispersed within the granite.

In thin sections (fig. 8) the ferroaxinite-bearing vein is seen to crosscut the large euhedral microcline and orthoclase feldspar crystals. Pyroxene and chlorite show evidence of hydrothermal alteration. The ferroaxinite is easily identified by its triangular, ax-shaped, euhedral crystals. In the vein's central vug, ferroaxinite overlies a selvage (fault gouge) of quartz, orthoclase, and microcline feldspar and is followed by fine-grained calcite.
Discussion

The axinite-group mineral occurrences in the Reading Prong metamorphics fit a regional pattern that has the same emplacement style and, probably, timing. The type of mineralization that is seen in these occurrences is similar to that found in alpine clefts. Alpine-cleft deposits develop in an existing open gash in which hydrothermal fluid infiltrates and recrystallizes the surrounding rock. The classic clefts are flattened cavities with maximum dimensions to 20 feet and, rarely, larger (Weibel 1966). They probably originate as en echelon vein arrays (Mitchell and Forsythe 1989), commonly known as tension gashes. Although some Reading Prong occurrences are localized in part in tension gashes, fissure veins are much more common. The origin of the open space is far less important than the nature of the country rock and the fluid flux rate. Cleft-type mineral assemblages suggest deposition in an environment where hydrothermal fluid flux is sluggish enough to minimize the introduction of chemical species from outside the immediate environment of the cleft.

At Lime Crest ferroaxinite appears to have been limited to a single fissure cutting through a granitic pegmatite for tens of feet. Because the granite was a less reactive rock than the amphibolites and skarns seen at other localities in the region, the vein assemblage is much simpler. Along the vein wall, adjacent to the country rock, are fine-grained quartz, feldspar, and chlorite. This material is a selvage of finely fragmented granite. The vein filling is ferroaxinite, quartz, and calcite. Ferroaxinite was probably able to crystallize, in spite of the nature of the immediate host rock, because there was sufficient fault gouge available and because of the calcium-rich nature of the nearby environs. The very low magnesium content of Lime Crest ferroaxinite may reflect the relative scarcity of ferromagnesian minerals in the granite.

The vein occurrences of axinite-group minerals in the Reading Prong are interesting in part because the source of boron is enigmatic. Boron is an uncommon element in most lithologies, generally less than 12 ppm. It has unique chemical properties that prevent it from being accommodated by nearly all rock-forming minerals. Therefore, boron may form its own minerals when present at relatively low concentrations.

Although boron minerals are known in the Franklin Marble and can be locally concentrated (Moore and Swihart 1990; Moore 1992), they are sparse at Lime Crest (Cummings 1997). They have not been recognized in the vicinity of the ferroaxinite occurrence or at any of the five other localities.

There are at least two localities, the Buckwheat Dolomite (Cummings 1988) and the Lime Crest quarry (Cummings 1997), where both Mississippi Valley-type lead-zinc and rock-forming mineral assemblages occur in the same structure. Both assemblages also occur in the Paleozoic sedimentary rocks, although the alpine-cleft type is very rare. The best exposure is in the Rickenbach and Epler Formations at Phillipsburg, New Jersey, where the assemblage contains minor tourmaline.

The only common rocks that contain significant amounts of boron are marine and some lacustrine shales and, locally, the Franklin Marble. These are two possible sources of boron associated with axinite mineralization. Within the lower Paleozoic section a boron source that must be considered is the Martinsburg Formation. Investigation of the boron isotopic composition of the alpine-cleft minerals may elucidate the origin of the fluids from which they formed and their relationship to the Franklin Marble (Moore and Swihart 1990).

Collecting Status

Although in the past Lime Crest quarry periodically held open-house weekends when collecting was allowed, currently all collecting activity is suspended.

ACKNOWLEDGMENTS

We would like to thank Warren Cummings, who made significant contributions to this article, deserving of coauthorship; Richard Bostwick and Steven Kuitem, who provided guidance and information; and Steven Chamberlain and Robert Cook, who reviewed the manuscript.

REFERENCES