

known to a Dr. Langstaff. Troost (1825) also reported it as a "*siliceous oxide of zinc*," but gave an erroneous description of the crystals. The first full description was published by Vanuxem and Keating (1824), but unfortunately they did not give it a mineral name, instead calling it "*siliceous oxide or silicate of zinc*." Thomson (1828, 1836), in describing Torrey's "*rhomboidal silicate of zinc*," published an erroneous analysis of a "*silicate of manganese*" (probably tephroite) which led to much confusion. In 1830, Lévy published the description of Belgian material and named it willemite. Shepard (1832b) gave the name *troostite* to the "manganese silicate" erroneously described by Thomson (1828). Subsequent studies were made by Delesse and Des Cloizeaux (1846) and Hermann (1849); the latter showed *troostite* to be identical with willemite.

Additional studies by Dana (1850), Wurtz (1851), Des Cloizeaux (1862), Cook (1868), Mixer (1868), and Rammelsberg (1875) served to provide a comprehensive characterization of willemite, considering the contemporary state of the science. Koenig (1890) described crystals of brownish-gray willemite in Franklin calcite, and he referred to them as *tephrowillemite*. Stone (1887) and Clark (1890) provided additional data. The nature of willemite was also of strong interest to those interested in the origins of these deposits, such as Ries and Bowen (1922) and Tarr (1929).

Palache (1935) provided a synthesis of these previous studies, added much original data, and noted previously unpublished information. There exists a very substantial literature on the synthesis of willemite, only a part of which is mentioned here. These include studies by Ingerson and Tuttle (1947), Klaska *et al.* (1978), and Hang Chin' *et al.* (1970). The use and misuse of the term *beta-willemite* was discussed by Frondel (1972) and is discussed below.

Crystal structure

The crystal structure of willemite was described by Zachariasen (1926), Bragg and Zachariasen (1930), O'Daniel and Tscheischwili (1944), Simonov *et al.* (1977b), Klaska *et al.* (1978), and Hang Chin' *et al.* (1970). Willemite is isostructural with phenakite and has as its basic unit an oxygen atom at the center of an equilateral triangle, with Zn, Zn, and Si at the three corners, repeated vertically along *c* with different orientations. These units are connected to form a hexagonal unit-cell.

WILLEMITE



Hexagonal, $R\bar{3}$, $a = 13.971$, $c = 9.334 \text{ \AA}$, $Z = 18$.

Willemite is queen of Franklin and Sterling Hill. It is by far the dominant Zn-silicate mineral at these deposits, is a very significant ore mineral, and is ubiquitous here. It occurs in primary assemblages, secondary assemblages, and late-stage assemblages and is common, indeed abundant, both geologically and as represented in mineral collections. Franklin and Sterling Hill have produced not only the bulk of the world's willemite specimens, but the finest ones as well.

Most of the scientific research on this species has been performed on local material. Willemite is now a much investigated mineral, but in the early years it was a much misunderstood one. The first brief description was by Torrey (1822a), who noted that this mineral, brought to him by Nuttall, and which he called "*siliceous oxyd of zinc*," previously had been

Description

Willemite occurs in superb crystals, commonly prismatic or barrel-shaped, from microscopic up to 40 cm in size. The early studies of its morphology were given by Penfield (1894) and Canfield (1907). Detailed additional morphological work was done by Palache and Graham (1913), Palache (1910, 1928a), Gordon (1922), and Palache and Berman (1927). Honess (1917) provided observations and illustrations of etch figures, and Lin and Shen (1993a, 1993b) provided data on the role of screw-axes in dissolution and the directional dissolution-kinetics.

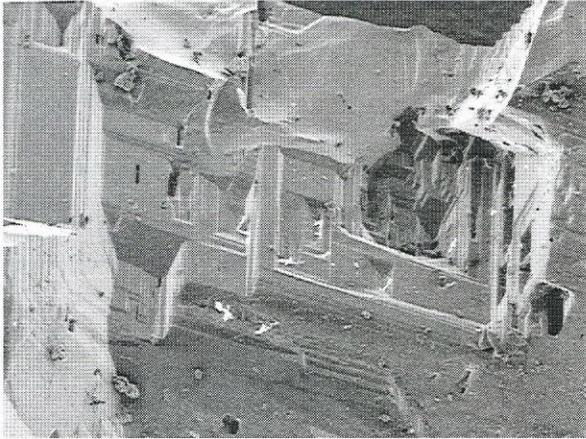


Figure 15-68. Etched prism surface of willemite from Franklin. Field of view is 0.5 mm in maximum dimension.

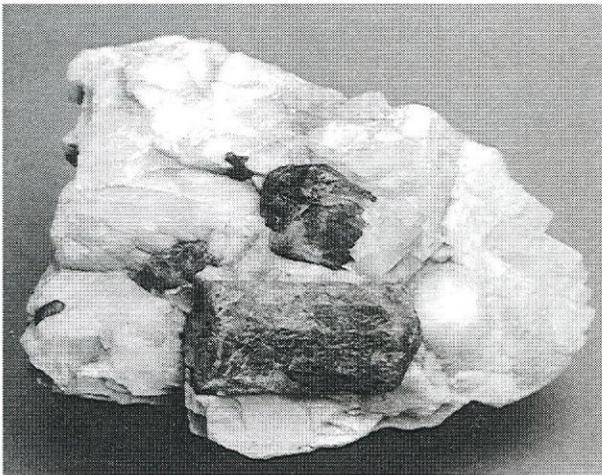
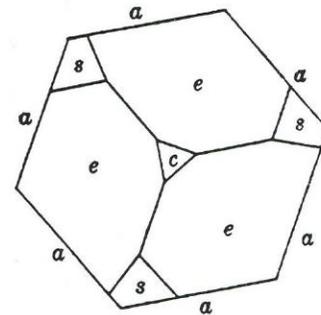
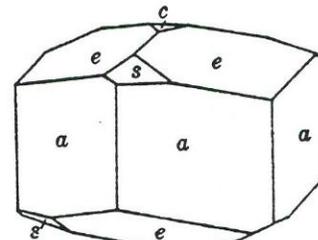


Figure 15-69. Crude hexagonal crystals of willemite in white calcite from Sterling Hill. Largest crystal is oriented with the view normal to the principal crystallographic axis, [0001]. Specimen is 8 cm in maximum dimension. Smithsonian Institution, #R3536-1. Photo by the author.

In general, primary willemite crystals in calcite are stout, commonly smooth-faced and barrel-shaped, and occasionally equant, tabular, or distorted (Figures 15-69 through 15-74).



A



B

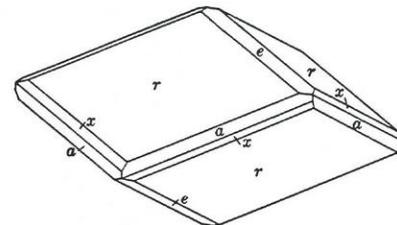
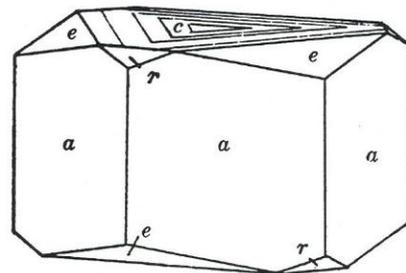


Figure 15-70. Crystal drawings of willemite from Franklin, showing stout or tabular habits. The upper two drawings are projections of the same crystal. Drawings are from Palache (1935) who provided crystallographic data.

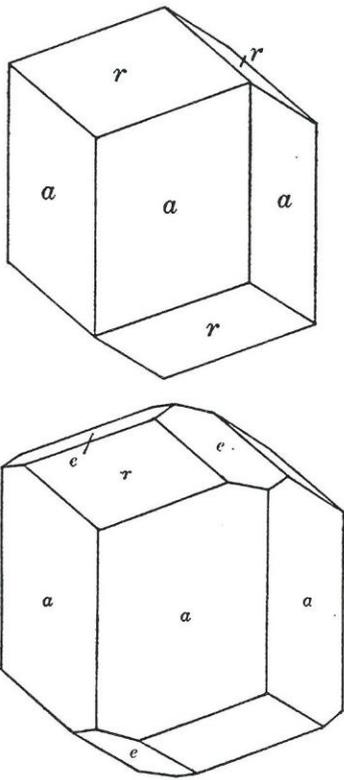


Figure 15-71. Crystal drawings of stout willemite crystals from Sterling Hill. Drawings are from Palache (1935) who provided crystallographic data.

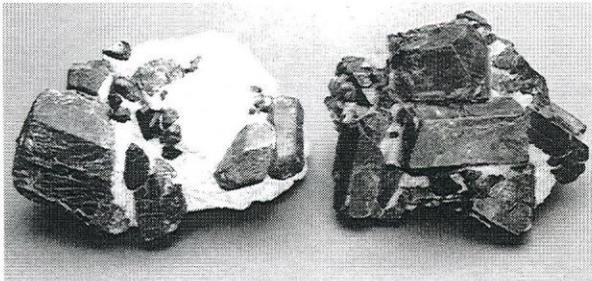


Figure 15-72. Prismatic to equant willemite crystals from Sterling Hill, associated with calcite (white) and octahedral crystals of franklinite (black). Specimens are 8 cm and 6 cm in maximum dimension. Smithsonian Institution, #C6184-1, #C6184-2. Photo by the author.

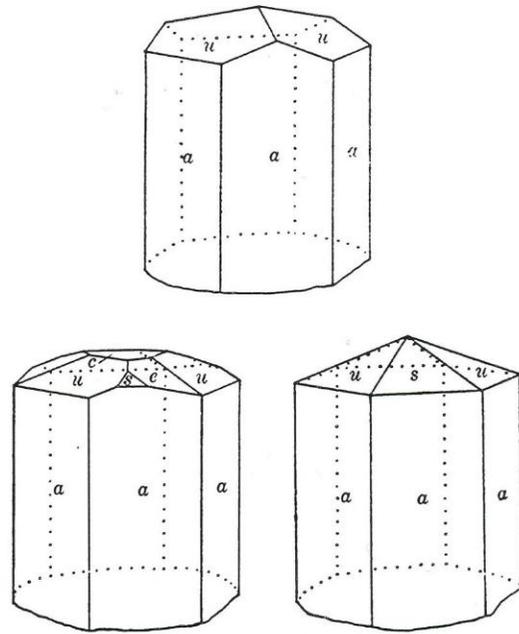


Figure 15-73. Crystal drawings of stout willemite crystals from the Trotter Mine. Drawings are from Palache (1935) who provided crystallographic data.

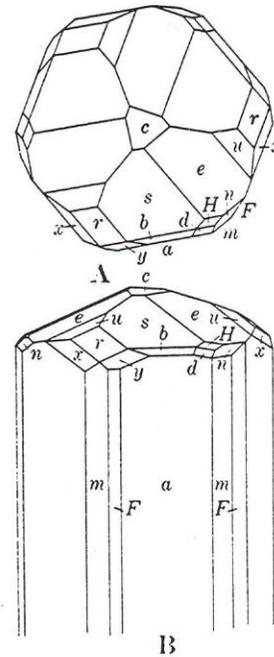


Figure 15-74. Crystal drawings of willemite from Franklin. These two drawings are projections of the same crystal. Drawings are from Palache (1935) who provided crystallographic data.

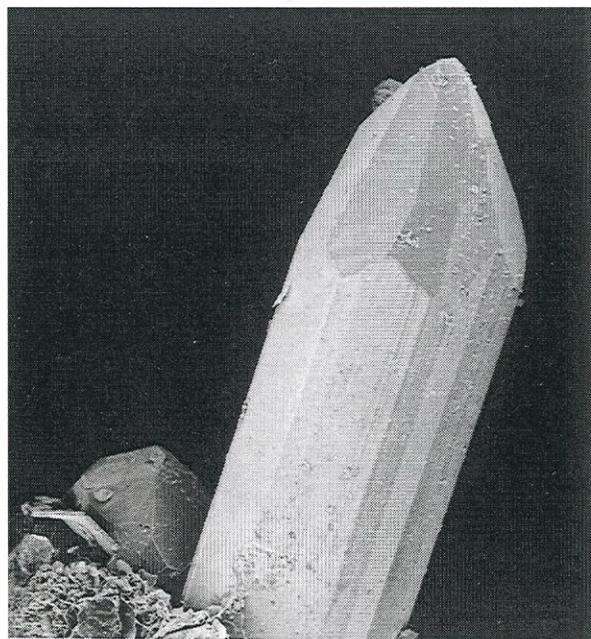
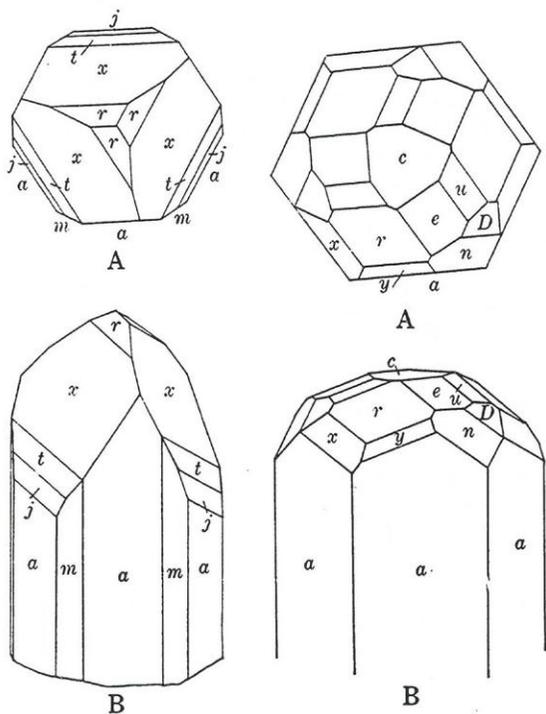


Figure 15-79. Prismatic crystal of willemite from Franklin, exhibiting multiple forms. Field of view is 1 mm in maximum dimension.

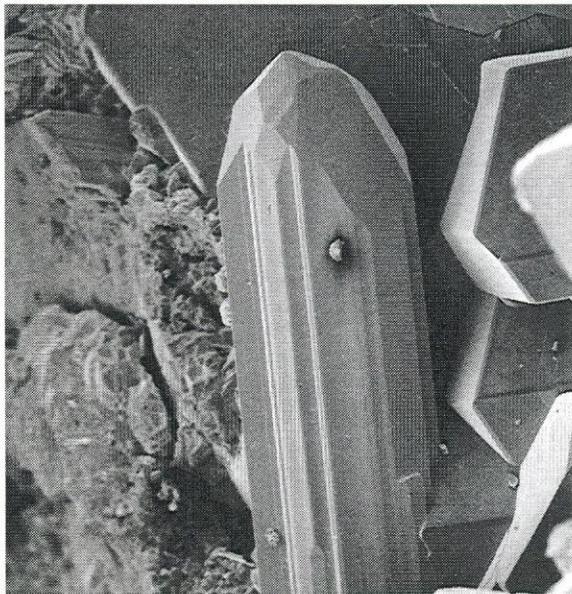
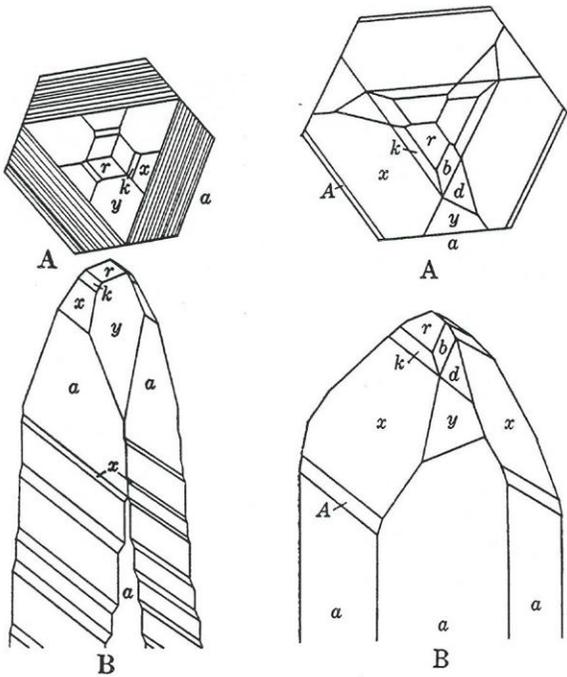


Figure 15-80. Prismatic, highly-modified, and striated crystal of willemite from Franklin. Field of view is 1.0 mm in maximum dimension.

Figure 15-78. Crystal drawings of Franklin willemite; here are shown sets of projections (A and B) of four crystals. Drawings are from Palache (1935) who provided crystallographic data.

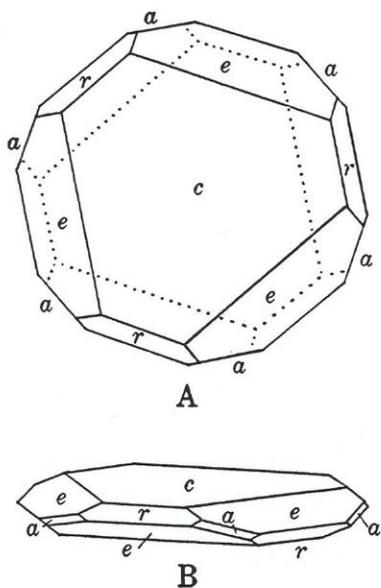


Figure 15-81. Crystal drawings of a tabular willemite crystal from Franklin. The two drawings are different projections of one crystal. Drawings are from Palache (1935) who provided crystallographic data.

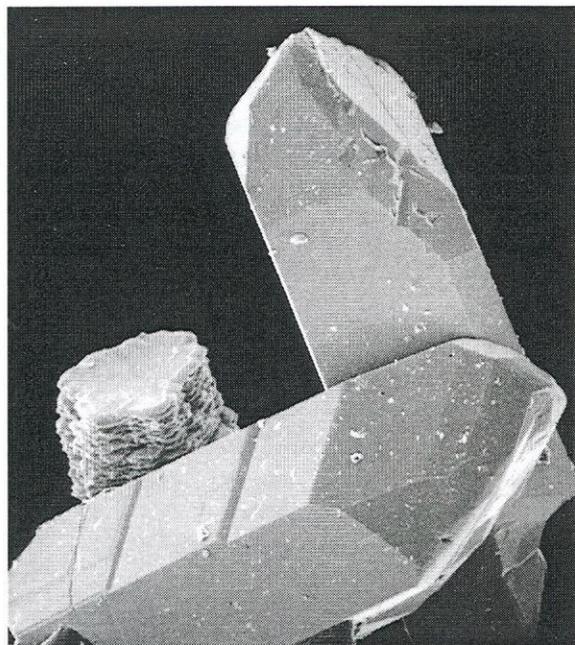
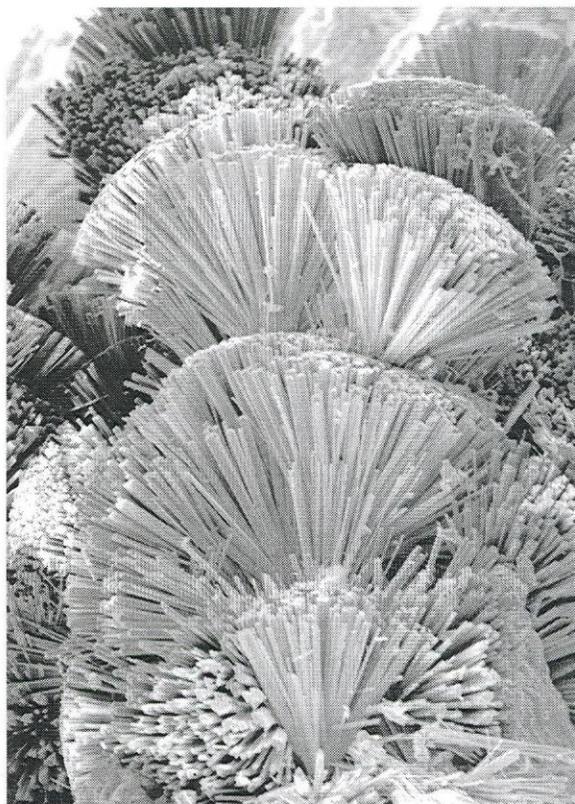


Figure 15-82. Two Franklin willemite crystals showing complex form-development. The layered aggregate of platy crystals is friedelite. Field of view is 0.9 mm in maximum dimension.

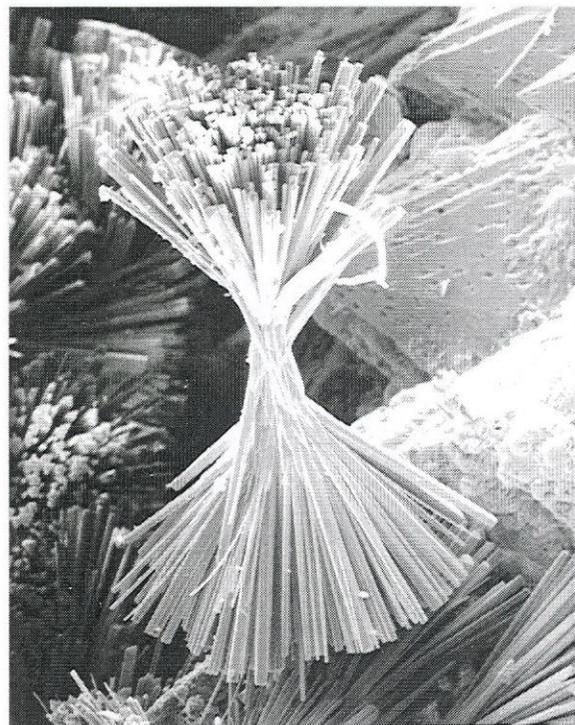


Figure 15-83. Clusters of acicular willemite crystals in radial divergent habit from Franklin. Field of view is 0.3 mm (upper photo) and 0.2 mm (lower photo), both in maximum dimension. See Figure 22-8.

Some acicular crystals may form mats of felt-like texture; some approach the texture of *mountain-leather* type tremolite; and many are delicate and microscopic (Figure 15-83). Palache (1935) noted that fibrous willemite was confined to carbonate veins.

Willemite has been cut as an uncommon, exotic gem. Fine-quality gemstones have been cut from orange-yellow willemite crystals: gems of 11.1 and 11.7 carats are in the Smithsonian Institution; one of 36.93 carats is in the Harvard Mineralogical Museum; and one of 6.28 carats is in the American Museum of Natural History in New York. Massive material may be quite clean internally and translucent and has provided some gemmy material for the cutting of chabochons. Gemological discussions of willemite were given by Pough (1974) and Webster (1975).

The bulk of local willemite, however, is in massive form as granular, anhedral crystals associated with franklinite and calcite in common, granular ore (Figures 12-1, 12-2, 12-3, and 12-11). Such granular aggregates of willemite may be locally quite pure and free from physical mixtures. Massive willemite, microcrystalline material, fibrous aggregates, and radial clusters of acicular crystals commonly line and fill secondary seams and fractures and are common in recrystallized assemblages.

The color of willemite is very variable. It occurs in green, reddish-brown, brown, yellow, white, colorless, orange, red, blue, gray, apparent black, and many intermediate hues, especially yellow-green. Red willemite from near Franklin pegmatites may have thermally altered color, and Metsger *et al.* (1958) has reported some green willemite from Sterling Hill to be thermally sensitive. The preponderance of local willemite is green or reddish-brown. In a very broad and general sense, willemite from Franklin is commonly green, and that from Sterling Hill is commonly reddish-brown or black. Exceptions to this general rule-of-thumb occur at both deposits, although primary green material is quite uncommon at Sterling Hill. The apparent color of green material is enhanced by its intense fluorescence in ultraviolet, discussed below, and thus specimens may appear greener than their true color when viewed in illuminations, like daylight, which are even partially ultraviolet-bearing. Reddish-brown willemite from Sterling Hill varies from deep dark red to a brownish-red; the apparent color is dependent to some extent on grain size. Reddish-brown willemite can be found associated with light greenish-yellow willemite; the color-boundaries may be sharp or diffuse.

Inclusions have played a major role in coloring willemite. Some colorless to light-yellow to light-green material may appear red from abundant microscopic inclusions of hematite (Graziani, 1978). Metsger *et al.* (1958) confirmed Palache's (1928b) observations that black willemite is colored by abundant microscopic inclusions of black franklinite, and reported that Sterling Hill red willemite is colored by abundant microscopic inclusions of red franklinite and that brown willemite is colored by a mixture of red and brown franklinite. This corrected, in part, the observations of Ries and Bowen (1922) who thought the red color resulted from inclusions of zincite. These inclusion-caused, apparent colorations were confirmed by Squiller (1976) except for brown willemite, which he suggested might be colored by franklinite of a distinct composition; this needs additional study. Squiller also found the color of the host willemite to vary with its composition, as noted below under chemical composition. The color of blue willemite has not been investigated.

Willemite generally has a vitreous luster which varies from slightly greasy to resinous in deeply colored varieties. There are two very indistinct cleavages, here unstudied; a conchoidal fracture is usually evident in glassy material. The density varies from 3.9 to 4.2 g/cm³, affected to some degree by inclusions. Optically, willemite is uniaxial, positive, with $\omega = 1.694$ and $\epsilon = 1.725$ (Palache, 1935). The photoconductivity of willemite was investigated by Herman and Hofstadter (1941), and the linear coefficient of thermal expansion was reported to be negative below 150° K (White and Roberts, 1988).

The most outstanding optical property of willemite is its fluorescence in ultraviolet. This phenomenon was noted in the Franklin Mine with the observation of the effect on willemite of electrical discharges (iron sparks). The fluorescence of willemite is inextricably tied to the history and mysteries of Franklin. It has been the focus or part of a number of studies, including but not limited to those by Kunz and Baskerville (1903), Spencer (1927, 1929), Palache (1928, 1935), Barrett (1934), Servigne (1943), Smith and Parsons (1938), Millson and Millson (1950), Gunnell and Schrader (1935), McDougall (1952), Metsger *et al.* (1953), Mutschler (1954), Cook *et al.* (1958), Jones (1961, 1964), Bostwick (1982, 1992), and Robbins (1983). Extensive references to other studies and discussions of activators are given by Robbins (1983) and Verbeek *in* Warren *et al.* (1995).

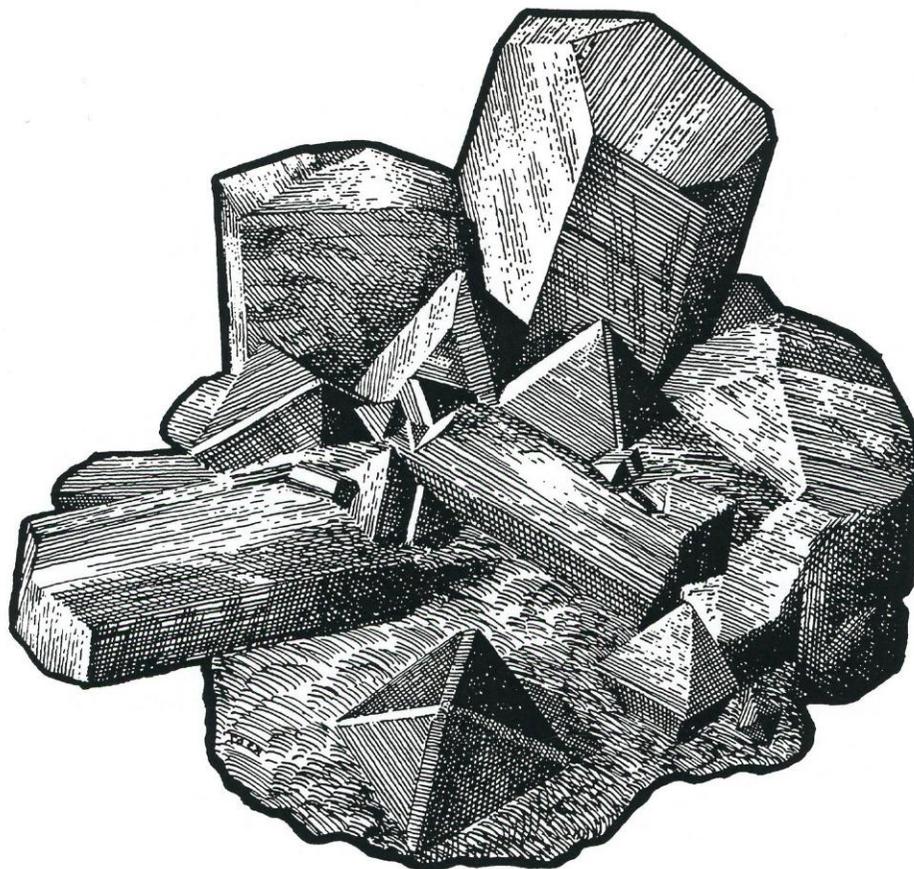


Figure 15-84. Drawing of prismatic willemite and octahedral franklinite crystals from Sterling Hill. Compare with Plate 13, drawing B, in Palache (1935). Drawing by Kenneth Sproson, used with permission.

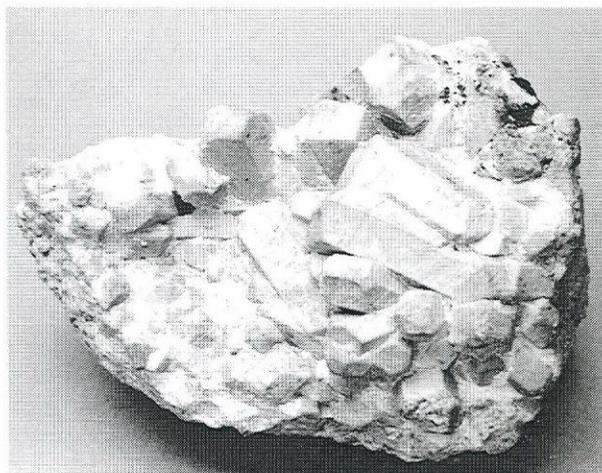


Figure 15-85. Prismatic willemite crystals in calcite (white) from Franklin. Specimen is 10 cm in maximum dimension. Smithsonian Institution, #116795. Photo by the author.



Figure 15-86. Willemite, rimmed by a symplectic intergrowth of zincite (dark gray) and hardystonite (white), in massive hardystonite from Franklin. Field of view is approximately 8 cm. Mineralogical Museum, Harvard University, #113599. Photo by Vic Krantz.

Willemite fluoresces green to yellow-green in shortwave ultraviolet; commonly, the fluorescence is similar, but less intense in longwave. Many specimens are phosphorescent to varying degrees. Green willemite commonly fluoresces much more strongly than the red varieties; fluorescence is somewhat subdued in very dark-colored material and markedly so in gemmy, dark-colored material. Red willemite does fluoresce; the gemmiest specimens exhibit a schlieren (flow) texture in ultraviolet. Some brown and "black" willemites fluoresce very weakly or apparently not at all. Non-fluorescent, colorless crystals are found occasionally in vugs and seams, but are rare. Secondary willemite, found in seams, crevices, veins, and in vugs in recrystallized assemblages, commonly has a more intense fluorescence and also has a substantially more intense and longer-lasting phosphorescence, relative to primary willemite. This is likely due to removal of some contaminants, such as Fe, during recrystallization processes, but the matter has not been investigated in detail.

Fluorescence has been reported in an anomalous willemite from Sterling Hill; it was known locally by the misnomer *beta-willemite* (Fron del, 1972), but is true willemite. The fluorescence of these crystals is strongly zoned. In shortwave ultraviolet they fluoresce orange to pale yellow in the exterior zone; the interior zone either fluoresces weakly or not at all. In the beam of the electron microprobe, the cathodoluminescence is orange in the exterior zone and light blue in the interior zone.

In general, the intensity of the response of willemite to an electron beam (cathodoluminescence) varies with composition, but not simply; it is strongest in specimens with MnO values between 2 and 8 wt. %. The intensity is diminished in specimens with even 1 wt. % FeO and also in specimens which have very little Mn, approaching end-member composition.

Strong triboluminescence was reported by Wick (1937), and the triboluminescence was noted as "faint greenish white" by Northup and Lee (1940), who also noted faint thermoluminescence with the same faint color.

Composition

Willemite is a zinc silicate mineral. Older analyses are summarized by Palache (1935) and show much Mn in solid solution for Zn, with Fe and Mg substitution more limited. Fron del (1972) noted exsolutions and inclusions of other minerals, and these may have possibly, in part, contributed anomalous results to some of the older analyses. Early analyses of "black" willemite should be dismissed; they are of mixtures and commonly contain components of some olivine-group minerals. Unpublished analyses by Lawson Bauer are presented in Table 5.

Recent analyses were given by Francis (1985b) of willemite exsolution in tephroite, and fifteen analyses of willemite from Sterling Hill ores were given by Squiller (1976), showing primary willemite to have high Mn-values. The writer's analyses of secondary, recrystallized willemites show them to have somewhat limited MnO values of less than 3.7 wt. %; most have MnO concentrations of 2.6 wt. %. The potential limits of beryllium solid solution in willemite were discussed by Essene and Peacor (1987).

For Sterling Hill material, Squiller (1976) found that red willemite has the lowest iron content; black willemite has the highest iron content; and brown willemite has intermediate compositions for iron and manganese. Therefore, the color of these different willemites, previously ascribed to compositionally different franklinite inclusions, may be due, in part or in whole, to the composition of the willemite itself. Squiller also noted a strong correlation for Fe in franklinite and adjacent willemite and a moderate correlation for Mn, suggesting, therefore, that the Mn and Fe ratios were fixed at metamorphism by local bulk-rock compositions.

Because little is known of the compositional variability of willemite from various assemblages and P-T environments, a number of specimens from the specific assemblages noted below were analysed; these data are presented in Table 6. Earlier analyses are given in Table 5. Specific analysis numbers are cited in the following section where appropriate. The willemite specimens which most closely approach end-member composition are those occurring as shards in a magnesioriebeckite breccia, radiating crystals in the carbonate veins, and the small 1-2 mm crystals, locally and erroneously called *beta-willemite*.

Species	SiO ₂	FeO	MgO	MnO	ZnO	Al ₂ O ₃	CuO	CaO	Total	Sample #	Locality	Reference
Willemite	28.29	0.32	0.13	3.27	67.12	0.50	0.02		99.65	n.g.	Franklin	Graziani (1978)
Willemite	29	0.15	5.2	2	66.0	0.01	0.05		102.41	n.g.	Franklin	Metcalf-Johanson (1977)
Willemite	27.34	3.00	0.59	2.66	65.77			0.14	99.50	C6192	Franklin	Bauer (unpublished)
Willemite	22.33	14.9		7.32	50.5					C6193	Franklin	Bauer (unpublished)*
Willemite			1.02	4.0	62.9					C6194	Franklin	Bauer (unpublished)*
Willemite			0.58	5.4	66.1					C6195	Franklin	Bauer (unpublished)*
Willemite		1.0		8.3	59.6					C6196	Franklin	Bauer (unpublished)*
Willemite		1.2			71.7					C6197	Franklin	Bauer (unpublished)*
Willemite		7.4		4.8	56.0					C6198	Sterling Hill	Bauer (unpublished)*
Willemite		0.9	3.87	4.0	62.4					C6200	Sterling Hill	Bauer (unpublished)*
Willemite	27.77	0.14	0.90	5.13	66.99			0.00	100.93	HU-38064	Franklin	Francis (1985b)
Willemite	28.23	0.03	2.72	2.14	67.43			0.00	100.55	HU-113721	Sterling Hill	Francis (1985b)

* recalculated, in part, from element wt. % analyses to oxides weight %. n.g. = not given.

Table 5. Chemical analyses of willemite.

#	SiO ₂	FeO	MgO	MnO	ZnO	Total	Sample #	Locality	Description
1.	29.0	0.0	0.4	5.0	67.6	102.0	C2828-19	Franklin	Bright green massive.
2.	30.0	0.0	3.7	2.6	65.8	102.1	163941	Franklin	Green granular.
3.	28.8	0.0	0.4	1.5	70.4	101.1	C6210-1	Sterling Hill	Medium green in vein, translucent ("sea-green").
4.	30.2	0.2	0.8	6.9	64.0	102.1	95476	Franklin	Dark red massive.
5.	29.2	0.0	0.1	2.7	69.2	101.2	93391	Franklin	Superb light green secondary crystals.
6.	29.3	1.0	0.0	0.3	72.0	102.6	C6177	Franklin	Light yellow crystal.
7.	28.8	0.9	0.0	0.1	70.9	100.7	C6177-1	Franklin	Light yellow crystal.
8.	29.4	0.0	0.3	8.3	63.5	101.5	83932	Franklin	Yellow, massive, in tephroite.
9.	30.3	0.2	3.4	6.2	62.0	102.1	164020	Franklin	Brown crystal in calcite.
10.	29.8	0.1	2.7	5.2	64.1	101.9	C2849-10	Sterling Hill	Black-coated, dark yellow, 6 cm prismatic crystals.
11.	30.2	2.3	1.3	3.4	65.1	102.3	147205	Sterling Hill	"Black" willemite.
12.	29.5	0.9	0.0	3.6	67.9	101.9	C6193	Sterling Hill	"Black" willemite.
13.	28.7	0.2	0.0	0.1	71.4	100.4	C6202	Franklin	Colorless, with blue magnesioriebeckite.
14.	29.3	0.4	0.0	1.2	70.3	101.2	C2834	Franklin	Yellow crystals in brown stilpnomelane breccia.
15.	29.9	0.5	0.0	1.0	70.6	102.0	95211	Franklin	Light greenish brown stout crystals in carbonate veins.
16.	27.9	0.0	0.0	0.2	72.0	100.1	C2828-5	Franklin	Radiating colorless willemite in carbonate veins.
17.	28.9	0.0	0.0	4.9	67.0	100.8	C6311-1	Franklin	Green vein in ore.
18.	29.4	0.0	0.0	1.2	71.1	101.7	C2845-7	Sterling Hill	25-50 mm green prismatic crystals in carbonate veins.
19.	29.2	0.6	1.5	2.4	67.9	101.6	146501	Sterling Hill	Brown equant crystals in calcite.
20.	29.4	0.5	1.8	3.0	65.7	100.4	144318	Sterling Hill	Brown equant crystals in calcite.
21.	29.5	0.1	0.9	5.7	65.5	101.7	144687	Franklin	Red massive with rhodonite.
22.	28.9	0.0	0.0	2.6	70.0	101.5	116797	Franklin	Superb light green glassy crystals on andradite.
23.	28.9	0.0	0.0	2.6	69.6	101.1	95341	Franklin	Superb light green glassy crystals in vugs with tephroite.
24.	29.1	0.3	0.0	0.3	72.0	101.7	R19156	Franklin	Light blue, translucent, on hematite.
25.	27.6	0.0	0.0	0.0	71.7	99.3	C6180	Sterling Hill	Light orange 1-2 mm crystals (locally called beta-willemite).
	26.9			73.1	100.0				Theoretical end-member composition

CuO less than 0.2 wt. % in all specimens.
 All specimen numbers are of the U. S. National Museum.
 Accuracy of data: ±3% of the amount present.

Table 6. Microprobe analyses of willemite by the author, with listing of source material.



Figure 15-87. Prismatic willemite crystals with octahedral franklinite crystal (black) in calcite (white) from Sterling Hill. This is an example of crystals revealed by the carving away of calcite (Figures 7-14 and 7-15). Specimen is 11 cm in maximum dimension. Mineralogical Museum, Harvard University, #85555B. Photo by Chip Clark.

Occurrence and paragenesis

Willemite is very abundant and widely distributed in both the Franklin and Sterling Hill orebodies and is the second most common ore mineral here; only franklinite is more abundant. It has been reported in xenoliths within the diabase dikes at Franklin by Emerson (1882), but only microscopically and only where those dikes are within the orebodies; this relation has not been examined by the writer. Willemite has not been found elsewhere in the Franklin Marble, local gneisses, or the Furnace Magnetite Bed. A comprehensive account of the orebody occurrences of willemite would be a volume in itself; what follows is a generalized summary which serves to introduce the major types of occurrences.

Primary ore

The dominant mode of occurrence of willemite at both deposits is as crude equant crystals, which are a principal constituent of the gneissic primary ore or the disseminated-granular primary ore, together with

franklinite, calcite and, less consistently, zincite (Figures 12-1 through 12-4, 12-11, 12-12, 12-13, 12-15, and 12-18). The proportions of these minerals vary considerably among the ore units; calcite varies to the greatest degree; and zincite may be absent. The size of the granular minerals varies; the average grain size is 2-3 mm, tending to be larger as the proportion of calcite in the ore increases. In general, such willemite granules are anhedral, but may be locally subhedral when the ore contains much calcite. Euhedral crystals are uncommon except where calcite is locally abundant. This extremely varied assemblage commonly occurs with a banded gneissic texture, as described by Frondel and Baum (1974). Some willemite occurs as exsolved platelets in tephroite at both deposits and is described under that species. Bustamite from Franklin also hosts exsolved willemite, together with johannsenite. Leucophoenicite, tephroite, and sonolite are commonly associated manganese silicates, together with minor amounts of accessory minerals. Additional information is provided in specific discussions of the ores.

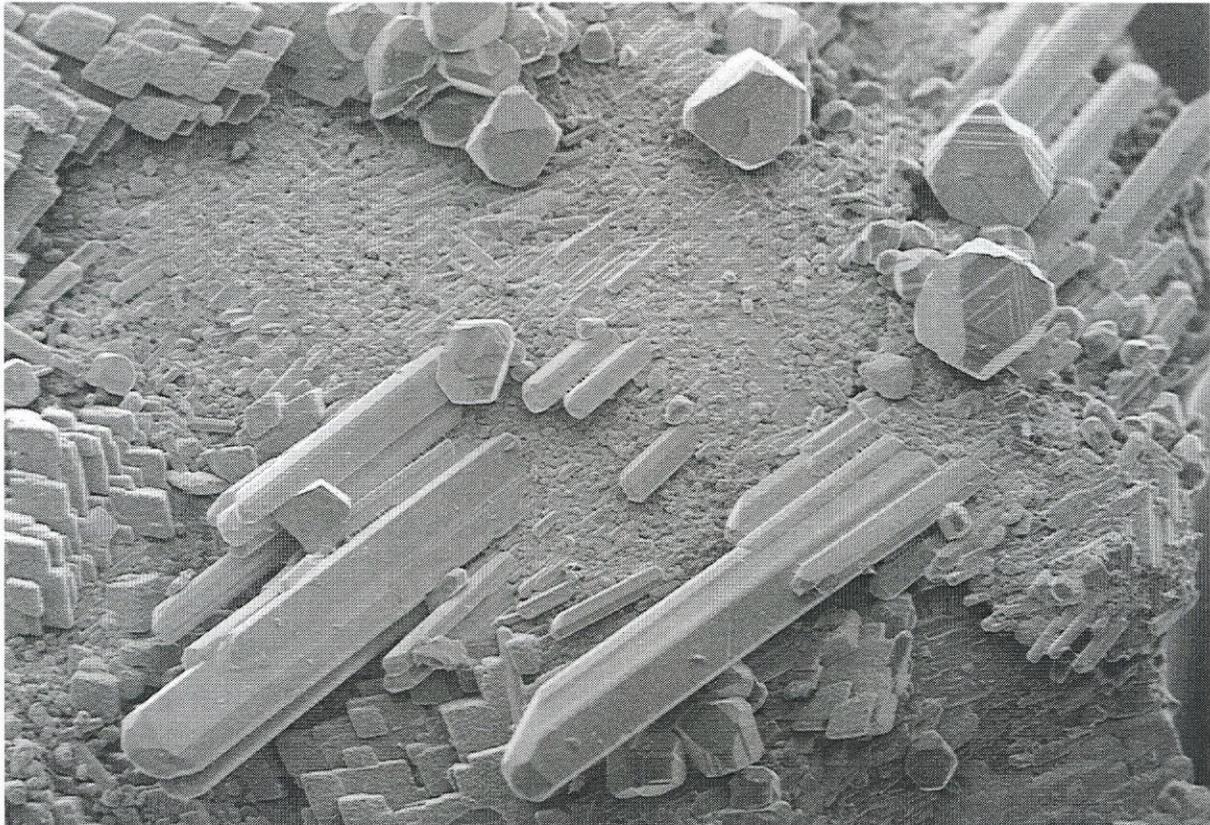


Figure 15-88. Parallel growth of willemite crystals, associated with franklinite, from Franklin. Field of view is 3 mm in maximum dimension.

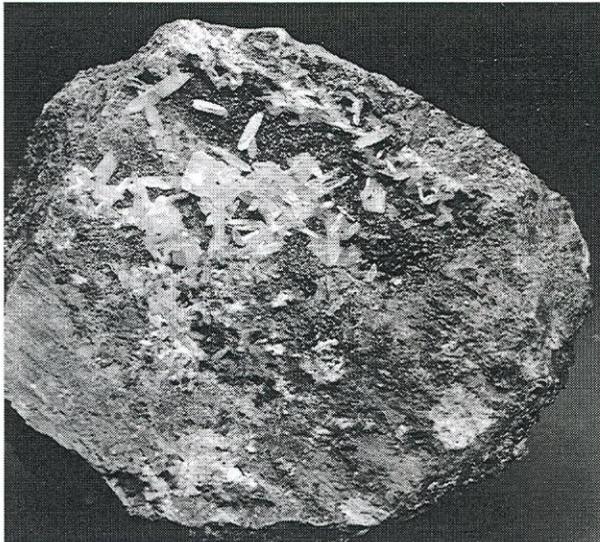


Figure 15-89. Prismatic crystals of willemite (light gray), on druse of andradite (small crystals, lustrous black). Specimen is 12 cm in maximum dimension. Mineralogical Museum, Harvard University, #89222. Photo by Chip Clark.

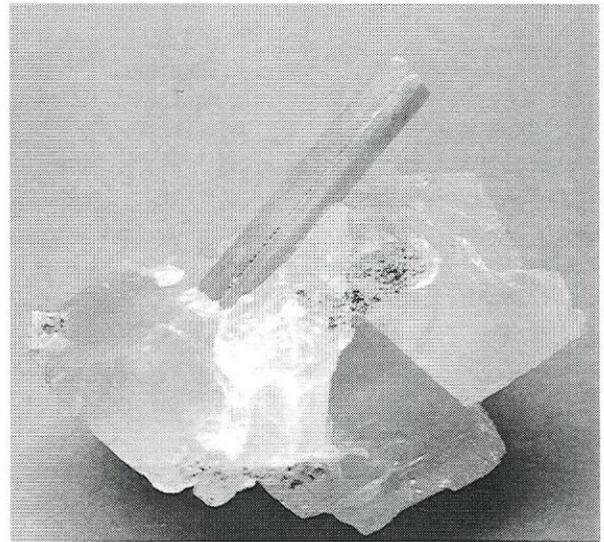


Figure 15-90. Prismatic, gemmy willemite crystal in colorless fluorite from Franklin. Specimen is 6 cm in maximum dimension. Smithsonian Institution, #C2834-4. Photo by the author.

Black willemite

Much black willemite has been preserved. It occurred in abundance at Sterling Hill as massive black material with minimal fluorescence (Figure 12-12), associated with loellingite, sphalerite, and fayalite (Figure 21-29) (Table 6, #11, #12). According to Metsger *et al.* (1958), black willemite comprised about a third of all willemite at Sterling Hill; it comprised the eastern half of the cross-member. Willemite from this black-willemite zone was the subject of a more detailed investigation by Davis (1993). Both primary and altered black willemite were studied by Makovicky and Skinner (1990); the assemblage needs much additional study. Black willemite also was found at Franklin, but much more sparingly; it occurred on the north end of the 750 level.

Recrystallized primary ore - simple assemblage

Franklinite, willemite, calcite, zincite, and tephroite are commonly found as apparently recrystallized material, occurring in coarse-textured assemblages with grain size up to 10-15 cm and no traces of relict gneissic banding (Figures 12-35 through 12-38). Such specimens are remarkably attractive and are prized by collectors.

Assemblages with calcium silicate units

Aside from the ore textures described above, willemite is very common in the enormous silicate units of the Franklin orebody. Here it is associated with a large number of silicate species. The principal minerals are rhodonite, andradite, hardystonite, bustamite, diopside, augite, mica, and nearly ubiquitous calcite and franklinite. Additionally, willemite occurs with most of the silicates from the recrystallized assemblages common in the northern end of the mine, such as hancockite, manganaxinite, datolite, the suite of lead silicates, and, especially, the "Parker-Shaft minerals."

Vein assemblages.

Veins of willemite are extremely common at both Franklin and Sterling Hill. They may parallel the ore bedding or crosscut it. See also the discussion herein of veins in the section entitled "Mineral assemblages." Such willemite veins are found in both primary and secondary assemblages. In the local collector's vernacular, they sometimes are called "ribbons" in allusion to their appearance; most have sharp and colorful contrast with the host matrix. Most vein assemblages have not been studied in detail. The

general classification used here is simple, complex, and carbonate-bearing. All are found at both deposits, but carbonate-bearing veins are more abundant at Franklin; see Figures 12-41 and 12-44 through 12-50.

The simple veins are those with pure willemite and few associated minerals; they are commonly found in the ore units. They result from solution, redeposition, and minor reworking of the ore. They are very attractive and found in most systematic collections. As with the banded ore, many of these willemite veins from Franklin are green to greenish-white (Table 6, #17); those from Sterling Hill reddish-brown willemite ore are green to greenish-white; and those from Sterling Hill black-willemite ore are yellowish. The material known locally as *beta-willemite* occurs in partially porous, yellowish aggregates with sphalerite; such masses may have formed in veins. It was found once, in the 1500 stope on the 430 level at Sterling Hill (Table 6, #25). An anomalous, light green, subtranslucent willemite, locally known as "sea-green willemite," occurs in 2 cm wide veins at Sterling Hill (Table 6, #3). Several veins were studied in detail by Makovicky and Skinner (1990).

The complex veins, which have willemite associated with numerous other diverse species, some of which are the dominant vein mineral, are very abundant in the silicate units of the orebodies as well as in the ore units. They commonly host substantial amounts of rhodonite, leucophoenicite (Figure 15-25), hedyphane, serpentine, and many other minerals. These are discussed in their respective sections.

The carbonate veins are distinctive for the presence of dolomite, which commonly contacts the primary ore. These veins also include numerous other species, and they form assemblages of varied texture. Serpentine and manganese carbonates, such as rhodochrosite, are commonly associated minerals. The relative abundance of willemite, carbonates, and serpentine varies widely. Serpentine, sphalerite, and rarely talc are the last minerals formed. In specimens wherein the walls of the veins are highly irregular, openings and vugs may occur and provide space for the free growth of fine crystals of rhodochrosite and willemite. Radiating rosettes of willemite, up to 8 cm in diameter, are found in such veins, and such radiating willemite commonly has an intense phosphorescence (Table 6, #16). Some such veins show contact effects with surrounding ore or rocks; most of these are readily discernible in visible light and/or ultraviolet radiation (Figures 12-48 and 12-49). Some of these veins penetrate the footwall marble.

Carbonate-vein occurrences of willemite occur at Sterling Hill as well, but are less well-known. The best of such occurrences is one containing light green, prismatic crystals, up to 4 cm long and 0.5 cm wide (Table 6, #18), which occur randomly arranged within very light-pink manganoan calcite. These have provided some of Sterling Hill's most esthetic willemite specimens. Other carbonate-bearing veins are also found at Sterling Hill.

Few specimens of Franklin blue willemite are known, but they are so anomalous as to deserve special mention. Willemite with an intense, light-blue color (Table 6, #24) occurs associated with calcite in a vein assemblage coating opaque hemispherules of hematite. Distinctly blue, massive willemite has abundant colorless inclusions or negative crystals. A very light-blue unstudied willemite is also known to occur at Franklin, associated with grossular and vesuvianite. An apparent light-blue willemite (color due to magnesioriebeckite inclusions) is noted under breccias. Some other specimens of willemite mixed with blue vesuvianite have been mislabeled as blue willemite; the mixture is obvious under ultraviolet.

Euhedral crystals in calcite

At Franklin, willemite commonly occurs as pinkish-orange crystals in calcite; euhedral franklinite crystals may be present as well. Such willemite crystals are commonly barrel-shaped, up to at least 9 cm, and are generally prismatic with a rhombohedron as the terminal form, though some may be equant (Table 6, #9). They commonly have a hexagonal cross-section, and there is a substantial variation in length-width ratio. Such crystals may have a thin surficial coating and may have rounded edges.

Similar crystals are found at Sterling Hill; some of these are distorted. In general, such Sterling Hill crystals (Table 6, #19, #20) occur in calcite of generally less intense fluorescence than that which hosts their Franklin counterparts. Although not known with certainty to have formed in a calcite matrix, deep yellow-orange, prismatic crystals, 1-3 cm in diameter and up to 10 cm in length (Table 6, #10), are known from Sterling Hill. They commonly have a black coating of variable thickness and appear to be black crystals at first glance. They may have come from the oxidized zone near the Noble and Passaic pits or from the footwall of the east limb near the East Shaft. Euhedral crystals in calcite may be quite large; crude hexagonal crystals, 15 cm wide by 40 cm long, were found in the north orebody, and gray barrel-shaped



Figure 15-91. Willemite crystals in calcite. Drawing by Dave Woods, used with permission.

crystals with yellow centers, up to 30 cm wide, were found on the 430 level in the west limb, both at Sterling Hill. The varietal name *troostite* has persisted for brown crystals from Sterling Hill (Figures 15-69, 15-72, and 15-87).

Secondary euhedral crystals

The morphologically best crystals of willemite are small ones, approximately 5 mm or much less in size, which occur freely grown in vugs, cracks, and openings in seams throughout the orebodies; they are commonly associated with carbonate minerals. The fine crystals illustrated by Palache (1935) are largely from such occurrences. They are commonly transparent, may be colorless, light green, or light yellow, and generally have intense fluorescence (Figures 15-76, 15-77, 15-79, 15-80, 15-81, 15-88, 15-89, 15-92, 15-93, and 18-9). These superb crystals are also notable in that they are associated with a great many of the rare and unusual minerals found at Franklin and Sterling Hill.

The assemblages are described in detail in specific sections of this text. Among the most beautiful willemite crystals from Franklin are those described by Palache (1928a, 1935); these occur as spectacular green, lustrous, prismatic, striated crystals with andradite, tephroite, barite, hodgkinsonite of unusual habit, and pyrobelonite. Those associated with the tephroite described by Gordon (1922, 1923a) (Table 6, #23) and the subsequently found similar 7 mm crystals which coat druse brown andradite (Figure 15-89) (Table 6, #22) are of equivalent quality. The best were found at Franklin.

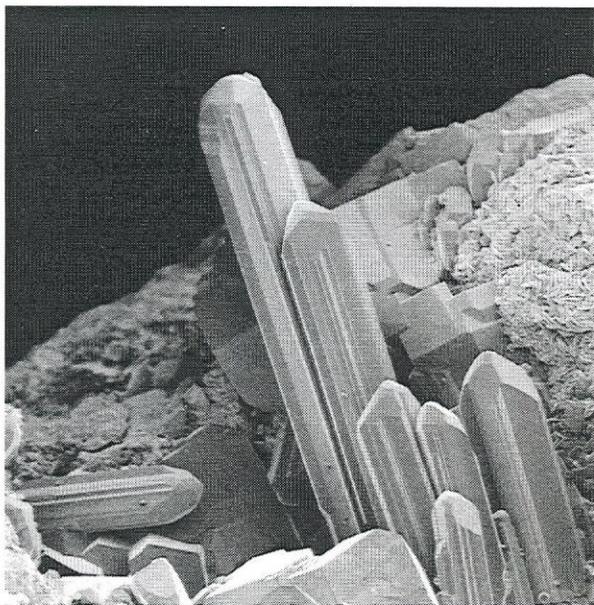


Figure 15-92. Cluster of willemite crystals in parallel growth from Franklin. Field of view is 3.8 mm in maximum dimension.

Breccias

Willemite is common in breccias, principally as shards and fragments, but also as the cementing medium, fracture fillings, and vug linings. Such breccias, although not uncommon, are not always recognized as such; the large grain or fragment sizes and small specimen sizes sometimes preclude recognition. Several Franklin assemblages of euhedral willemite in breccias have been preserved and are noteworthy; these are listed below.

a) a dull brownish-gray stilpnomelane breccia enclosing shards of andradite and superb sharp euhedral, light yellow crystals of willemite from the Trotter Mine (Table 6, #14).

b) Light yellow, slightly resorbed prismatic willemite crystals, up to 5 cm, in a fluorite-willemite breccia.

c) Colorless to apparently light-blue willemite (Table 6, #13), comprising part of a breccia of sphalerite, calcite, magnesioriebeckite, and lennilenapeite.

d) Bright-green, broken prismatic crystals of willemite cemented within a barysilite matrix.

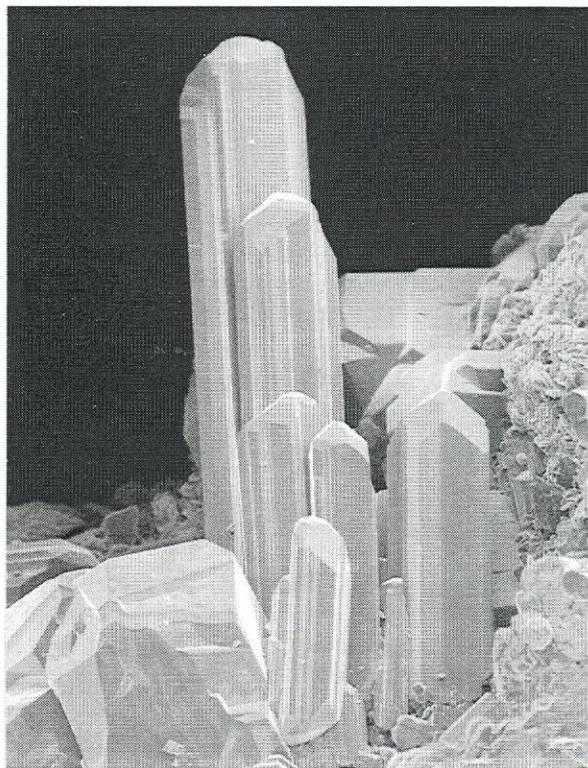


Figure 15-93. Prismatic willemite crystals in parallel growth from Franklin. Field of view is 2.5 mm in maximum dimension.

Special comments

Metsger *et al.* (1958), supported by Squiller (1976), have reported the replacement of willemite by tephroite and by serpentines. Some apparent willemite, especially from the east limb at Sterling Hill, may be a mixture of several of these components; replacement is commonly incomplete. Such replacement may have been locally extensive and may have contributed to the formation of some secondary zincite. Makovicky and Skinner (1990) have described several altered willemite assemblages and suggested that the alteration of red willemite may have been an active agent in the formation of secondary manganese minerals; additional discussion is given by Davis (1993).

Willemite is apparently quite soluble in hydrothermal solutions and is highly mobile. The literature on these deposits contains scant mention of weathered or surficially altered willemite, but Roy and Mumpton (1956) and Takahashi (1960) provided experimental data on the solubility and alteration of synthetic willemite. Altered surfaces can be blackish, and Palache (1935) noted a possible alteration to hemimorphite.

The above classification is an admittedly forced, abbreviated, and inadequate one; others are no less valid. Willemite is ubiquitous at these deposits and is found in nearly every available mineralogic niche. Much willemite occurs in slips, fault gouges, tectonic debris, and in many other occurrences, not all of which are mentioned here. Within the calcium silicate units at Franklin, much willemite was highly mobile, forming blebs and rounded aggregates.