

## DESCRIPTIVE MINERALOGY OF PUGH QUARRY, NORTHWESTERN OHIO: BARITE AND CELESTITE<sup>1</sup>

DAVID F. PARR<sup>2</sup> and LUKE L. Y. CHANG, Department of Geology, Miami University, Oxford, OH 45056

**Abstract.** Two sulfate minerals, barite and celestite, were identified in the Devonian rocks at Pugh Quarry. The barite occurs commonly as rosette-like clusters with wide variety of colors and crystal habits. Unusual features include paired crystals and hollow crystals. The former consist of two barite crystals growing parallel with each other on the dolostone matrix, and the latter only of a thin wall of barite commonly marked by cross striations. Celestite crystals have two different colors. The gray-blue and blue crystals are prismatic to blocky and occur as well-formed individuals, whereas the colorless and white crystals are tabular to bladed and occur as distinct individuals and as compact clusters.

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This is the fourth and last part of the mineralogy studies of Pugh Quarry. The quarry is located in the SW $\frac{1}{2}$ , SW $\frac{1}{4}$ , Sec. 6, T.4N, R.9E in Milton Township, Wood Co., Ohio, and has quite a diversified mineral assemblage. In addition to the barite and celestite described in this paper, there are the sulfides: marcasite, pyrite, and sphalerite (Parr and Chang 1977, 1978), the carbonates: calcite and dolomite (Parr and Chang 1979), and fluorite (Parr and Chang, 1979).

### BARITE

Barite is far less common than calcite at Pugh Quarry. It is most abundant in the mineral zone (Parr and Chang 1977) and also occurs less abundantly in isolated cavities stratigraphically lower than the mineral zone. The highest concentrations of this mineral are in the eastern portion of the north wall of the quarry.

*Relation to Host Rock.* Most thin-sections revealed a thin zone of calcite, 2 to 3 mm thick, separating the barite from host rock (fig. 1). The calcite zone consists of crystals of the "small type" (Parr and Chang 1979), and calcite terminations project into the basal por-

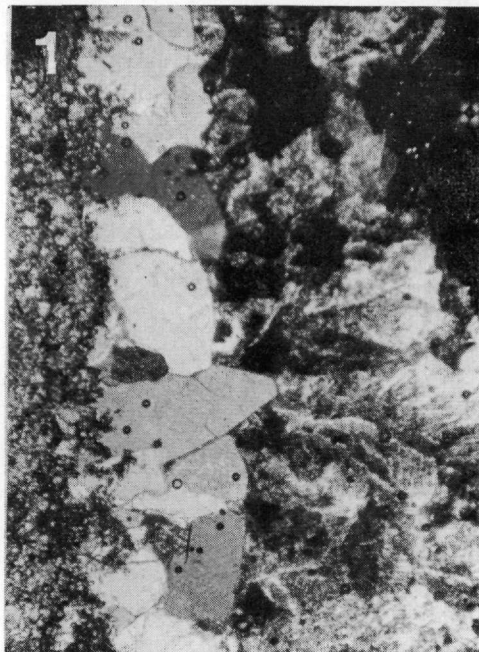


FIGURE 1. Thin section, crossed nicols. Barite on small calcite on dolostone. Note euhedral small calcite crystals forming a separating layer between the barite (right) and the dolostone (left). ( $\times 25$ )

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<sup>2</sup>Present Address: Department of Geology, Wisconsin State Univ., Superior, Wisconsin 54880.

tion of the encrusting barite. Rarely the barite can be seen to be intergrown with these small calcite crystals.

In other specimens, barite was found

to form directly on dolostone, but no evidence indicates the replacement of dolostone by barite. Some dolostone rhombs are enclosed in barite near the dolostone-barite interface (fig. 2). These



FIGURE 2. Thin section, crossed nicols. Barite on dolostone. Note sharp dolomite rhombs enclosed in the barite. ( $\times 25$ )

rhombs have sharp borders and are several times larger than the rhombs composing the dolostone matrix. These large dolostone rhombs may have formed contemporaneously with the barite enclosing them.

*Color and Size.* The barite found at Pugh Quarry occurs in a wide variety of colors: colorless, cream, cream-white, white, pale blue, blue-gray, blue-green, green-yellow, and yellow-brown. More than one color can be observed as zones within a single crystal or cluster of crystals. Commonly, the barite is cream, white, or pale blue. All barite from the quarry is translucent, and many specimens are transparent near the thin edges of the crystals. Luster of the crystals and crystal aggregates is generally from glossy to pearly and less commonly dull to earthy.

Barite rarely occurs as individual crystals in Pugh Quarry. Most common are rosette-like clusters of parallel and sub-parallel crystals. These clusters range from a few millimeters to as much as 7 centimeters in maximum dimension. Encrustations as much as 5 mm thick and blocky to tabular aggregates were also found. Diameters of the relatively rare single crystals range from less than 1 mm to more than 2 cm.

*Habit and Form.* The crystal habits of the barite from Pugh Quarry are extremely varied. Crystal aggregates, characterized by curved surfaces, are prevalent, and their crystal surfaces are irregular with vicinal faces commonly visible. These crystal aggregates were formed by parallel, sub-parallel, split-sheath, and step-growth of a small number of common barite forms (figs. 3 and 4) that were defined on the basis of their relation to cleavage planes and approximate measurements made with a contact goniometer. Invariably,  $\{001\}$  and  $\{210\}$  are present with the modifying forms  $\{010\}$  and  $\{100\}$  occurring rarely. The curvature of the crystal faces and the multiplicity of the crystal clusters precluded the use of the optical goniometer in making interfacial angle measurements.

The basic habit of Pugh Quarry barite is the tabular to plate-like rhombic prism. These rhombic units were rarely found separately, but rather combined together to form paired crystals, oblong fourlings, rosettes, spike clusters, crested aggregates, and layer-and-spike aggregates. Barite also occurred as so-called hollow crystals.

Paired crystals consist of two barite crystals growing parallel with each other on the dolostone matrix (fig. 5). The two crystals are connected by a barely visible coating of barite on the dolostone. This film of connecting material is present on the matrix only in the small space between the two crystals. Different generations of mineral growth are discernable as zones of white barite sandwiched between two layers of clear barite, which consist of many wedge-shaped crystal terminations arranged in an imbricate or step-like structure. The multiple terminations are all part of a single crystal unit (fig. 5). It is apparent

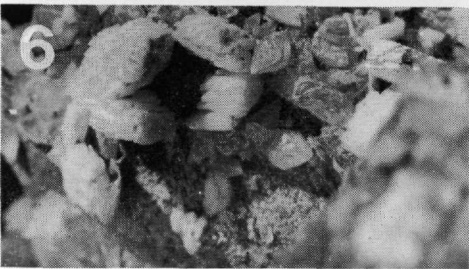
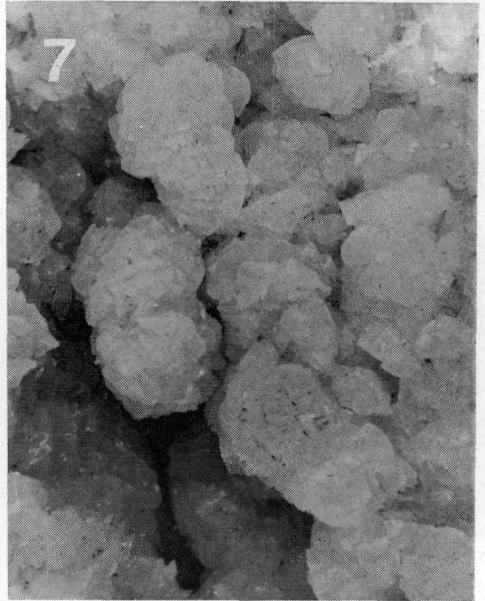
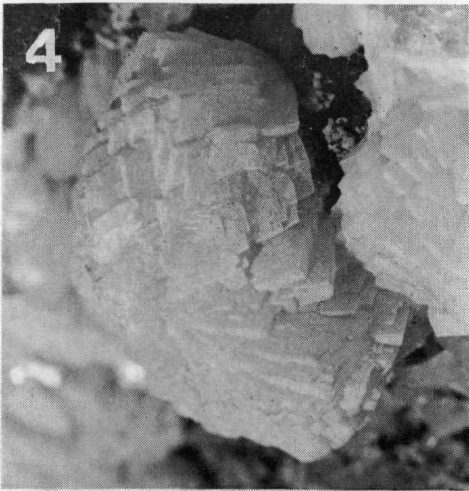
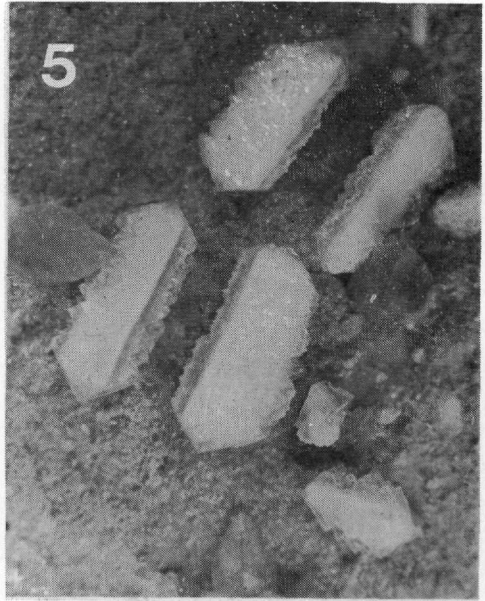
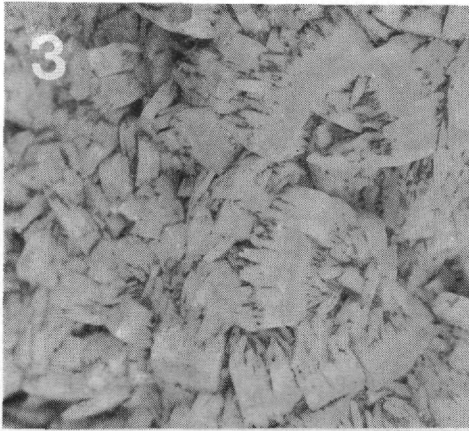


FIGURE 3. Barite crystal aggregates. Note split sheath and parallel-subparallel growth of aggregates. Cross-section shape of aggregates is rhombic. ( $\times 3.3$ )

FIGURE 4. Barite on dolostone. Parallel and sub-parallel step growth is clearly visible on these compound crystals. Note rhombic character of individual crystal units making up larger clusters. Individual rhombic crystals are arranged in a manner giving cluster curved surfaces resembling saddle crystals of dolomite. ( $\times 3$ )

FIGURE 5. Barite and small calcite on dolostone. Paired barite crystals. Note the parallelism of each pair, the zone of clear barite, and the imbricate or step-like arrangement of the barite terminations. ( $\times 8$ )

FIGURE 6. Barite on marcasite. Note the characteristic central opening in the clusters, the variety of shapes, and the varying stages of development. ( $\times 4$ )

FIGURE 7. Barite crystal aggregates. Composed of a basic unit, the rhombic prism, these rosette clusters are common in Pugh Quarry. ( $\times 1.5$ )

from the parallel arrangement of the two individuals constituting the pair that they are oriented to the same axial system.

The origin of the paired crystals is not completely understood. Two hypothetical explanations are presented. The first involves three steps: growth, resorption, and growth. During the first stage, a barite crystal developed that encompassed an area equal to that presently occupied by the crystal pairs. A change in the solution chemistry then caused much of this crystal to be dissolved. The barite that was not taken into solution consisted of the white material now sandwiched between the two clear barite layers. During the third stage, clear barite was deposited on the remaining portions of the original crystal, the white material. The remnants of the original crystal provided the similarly oriented seed crystals on which the clear barite was formed producing parallel paired crystals. The sharp crystal termination precludes the possibility that the paired crystals are remnants of larger crystals, which have been partially dissolved away. The second is that the paired crystals are simply a phenomenon of growth. The parallelism of the paired crystals may be explained by the connecting layer of barite on the matrix between the crystals. This layer carried the crystallographic orientation code by which the two crystals developed.

Barite crystal clusters consisting of 4 individual lens-shaped aggregates of sub-parallel crystals arranged to form a habit resembling short, flattened tubes were observed (fig. 6). These fourling clusters are less than 1 cm in maximum dimension. The arrangement of the 4 individual aggregates resulted in an opening in the middle of the cluster. The 4 component clusters may be nearly separate from one another or they may merge together making the separate character of the individual units minimal. The nature of this relationship is not understood, but numerous specimens show fourling, lens-shaped clusters, suggesting that coincidence is not a valid explanation.

Rosettes as much as 1 cm in diameter are one of the more common barite habits found in Pugh Quarry (fig. 7). These do not resemble the classic barite rose

sand crystals from near Norman, Oklahoma. The rosette crystal clusters, generally creamy white, are formed by split crystal growth, yielding clusters of curved crystals which fan out towards the margins of the clusters. Along the cluster margins, the area of maximum spread, the rosette appears to be composed of numerous individual crystals that taper toward the cluster center.

Some of the individual crystal cluster composing the rosettes have a distinct sheath-like appearance, whereas others show curvature resembling the classic dolomite saddle crystals (fig. 4). Close examination of the rosettes reveals that the rhombic prism is the pervasive form of the individual platelets in the clusters. Commonly, the rosette clusters exhibit a crude rhombic outline. There is no indication that these crystal clusters are anything but the result of primary crystal growth.

One of the more unusual barite habits found at Pugh Quarry are spike clusters with length ranges from about 1 cm to 5 cm (fig. 8). Numerous small rhombic prisms apparently were the building blocks of the larger more complex spike-like clusters. The arrangement of these prisms in parallel and sub-parallel growth gives many of the elongated spike clusters a Christmas Tree appearance (fig. 9). Commonly, the spikes are bounded by numerous terminations of the rhombic prisms arranged in an imbricate manner. Sharp, chisel-edged terminations commonly form the apices of the spike-like cluster (fig. 10). Other spike clusters branch into many smaller spikes, each with its own chisel-edged terminations, giving some specimens a delicate leafy appearance resembling the leaf portion of pineapples. Some spike-like clusters produce a cockcomb or crested appearance at the terminations of the cluster. These terminations are not restricted to the spike clusters, but are commonly found on other types of barite clusters.

The layer-and-spike aggregate habit is shown in fig. 11. Both the layers and the separating spikes are clusters of smaller crystals and the rhombic prism is the basic crystal form. These spikes may branch in much the same way that the larger spike structures do. This

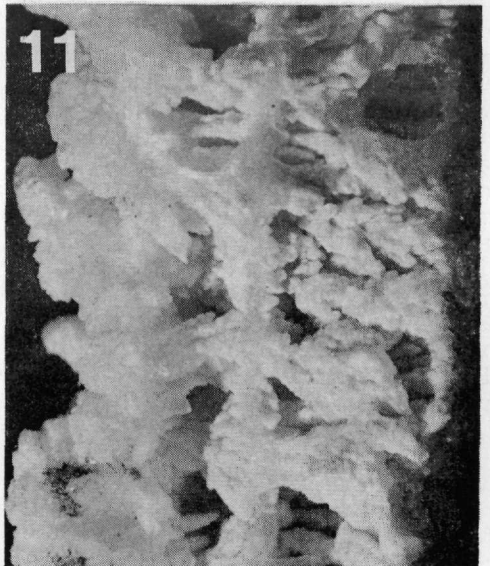
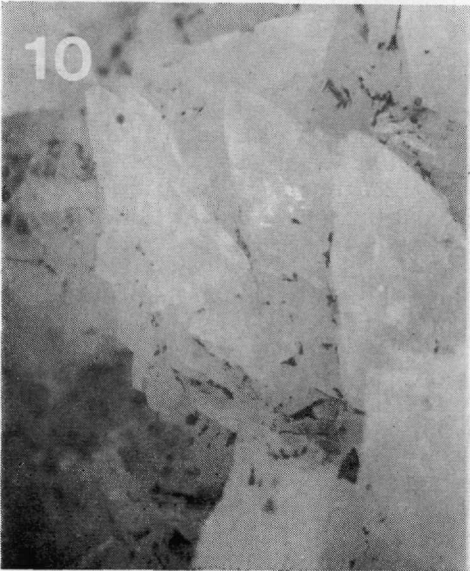
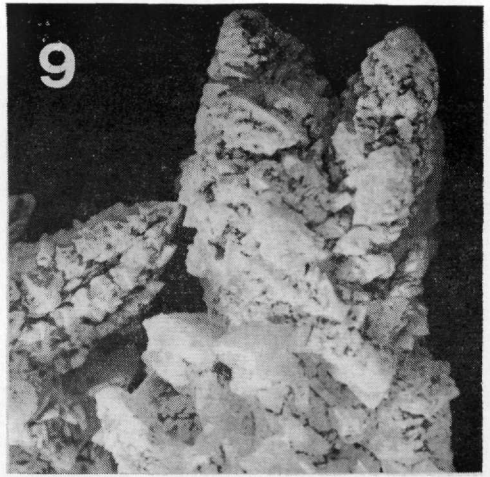
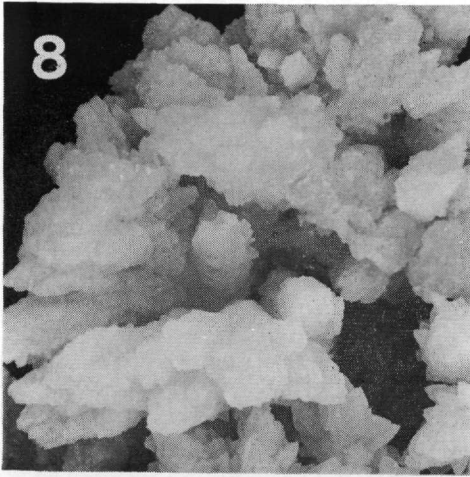


FIGURE 8. Barite. Cluster of barite crystals composed of many smaller spike-like barite clusters. Specimens of this type have a delicate leafy overall appearance. ( $\times 1.2$ )

FIGURE 9. Barite. Spike-like compound crystal cluster with a rough Christmas Tree appearance. ( $\times 3.5$ )

FIGURE 10. Barite. Spike-like clusters showing the sharp chisel edge terminations of the clusters. ( $\times 5$ )

FIGURE 11. Barite. Note the spike-like character of the clusters that separate the layers of barite. ( $\times 3.4$ )

habit may have resulted from slight periodic variations in the levels of the solutions from which precipitation took place, and the separating spikes may have developed during periods of changing solution levels.

The most unusual habit in which Pugh Quarry barite was found can best be

described as hollow crystals (figs. 12 and 13). These crystals, all of which are white, range in size from 0.5 mm wide and 2 mm long to 3 mm wide and 8 mm long. Cross sections of the crystals are square to slightly rectangular and longitudinal sections vary from canoe-shaped to rectangular. The hollow crystals con-

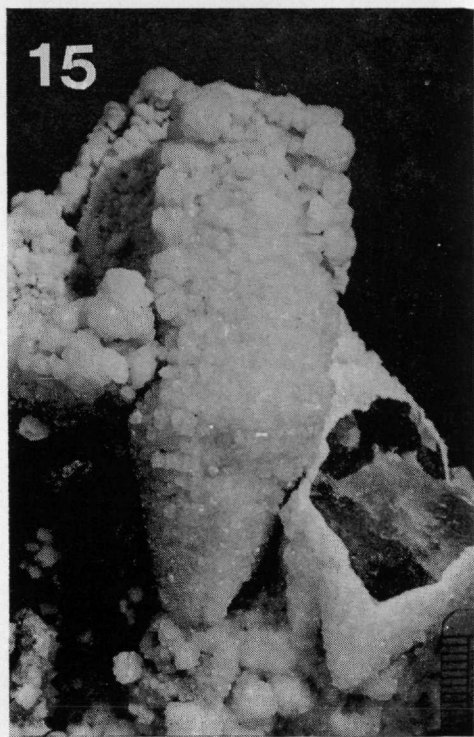
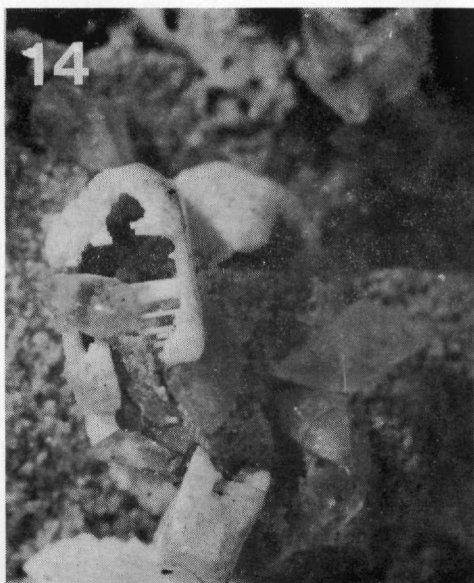
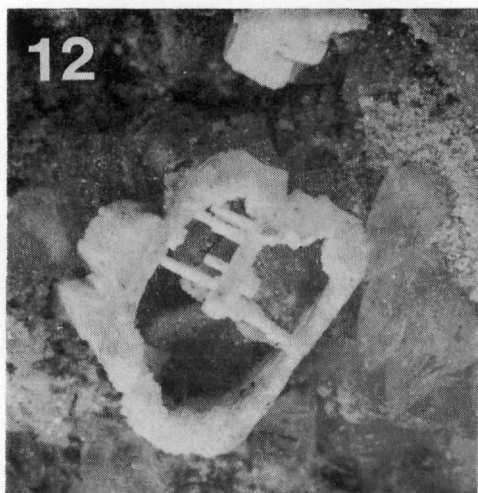


FIGURE 12. Barite hollow crystals and small calcite crystals on dolostone. Note delicate needles of barite extending between opposing walls of barite in place of a solid wall. ( $\times 8.2$ )

FIGURE 13. Barite hollow crystals and small calcite crystals on dolostone. The impingement of calcite crystals into walls of barite and the protrusion of the calcite through the barite walls is indicated by arrows. ( $\times 7$ )

FIGURE 14. Barite hollow crystal and small calcite crystals on dolostone. Note barite needles enclosed in a small calcite crystal. ( $\times 9$ )

FIGURE 15. Barite on large calcite. Note heavy accumulations of barite on interfacial joins of the calcite crystal. ( $\times 1.3$ )

sist only of thin walls of barite commonly marked by cross striations. Many individuals appear to be well-formed, solid crystals, but the thin walls were easily broken revealing hollow interiors. Many individuals showed one or more of the walls to be incomplete, but with fine needles of barite commonly extending across the hollow crystals in place of a well-formed wall (figs. 12 and 13). Similar delicate barite needles were observed to protude from the walls into the open hollow of the crystals.

The relation between small calcite crystals and hollow barite crystals is complex; well-formed small calcite crystals are commonly found inside the hollow barite crystals (fig. 13). Small calcite crystals are attached to matrix in the usual manner and commonly project through the walls of the hollow barite crystals with part of the calcite crystal inside the hollow barite crystal, and part outside (fig. 14). In these specimens, the walls of the hollow crystals can be seen to extend partially into the calcite crystal, suggesting simultaneous precipitation of the two minerals. The sharp, clean appearance of the calcite indicates that the crystals grew in open space, free from impingement except for the small area at the wall of the barite hollow crystal.

Several possible explanations for the origin of hollow barite crystals have been proposed. The most obvious and initially the most appealing hypothesis is pseudomorphism, which suggests that the barite was precipitated over pre-existing crystals which have since been removed by solution. This explanation accounts for the external morphology of the hollow crystals, their hollow character, and thin wall, but does not explain the presence of the well-formed calcite crystals within them or the acicular barite extending across the central void. Another hypothesis considers the hollow crystals as shell-like remnants of previously existing barite crystals, where the central portions have been dissolved out. If so, why were only the central portions of the original barite crystal dissolved away? It is possible that the hollow barite crystal is the primary product of a growth phenomena and that the hollow

crystals are essentially unchanged from the time they were formed.

Barite is a common encrusting material on large calcite crystals; its encrusting layers may be as thick as 5 mm (fig. 15). The thickness of the barite on a single calcite crystal face is generally uniform, but the encrustations appear to have an affinity for the interfacial joins and the terminations of the calcite crystals.

*Microscopic Features.* In thin section, tabular and bladed barite crystals are characteristically arranged in radiating clusters and randomly-oriented, matted aggregates (fig. 16). Plumose structures are common (fig. 17), with each made up of many curved, frond-like crystal units, all with nearly the same crystallographic orientation. The slight variations of orientation give the individual units optical distinction, and the overall effect is that the plumose structure has extremely undulatory extinctions. This type of extinction is prevalent in thin sections of all barite found at Pugh Quarry.

Zoning is apparent in thin sections of barite crystals and crystal aggregates and resembles chevron strips, particularly in thin-sections (fig. 18). In these sections, thickness variations result in vivid interference color differences with zones that can be seen clearly in both plain and polarized light. In addition to the color zones, white opaque zones were observed in many barite crystals (fig. 19). They appeared to be depositional and are probably not the result of secondary alteration. Hydrochloric acid applied to the opaque zones of barite did not indicate the presence of carbonate. Frondel (1935) described a similar type of zoning in white opaque barite at other localities. His chemical analyses showed that they were essentially pure barium sulfate. X-ray diffraction analyses confirms Frondel's findings. The unusual appearance of the zones is probably related to poor crystallinity or to large numbers of fluid inclusions contained therein.

#### CELESTITE

Celestite was found only in the eastern portion of the quarry. Gray-blue and blue celestite crystals occurred predomi-

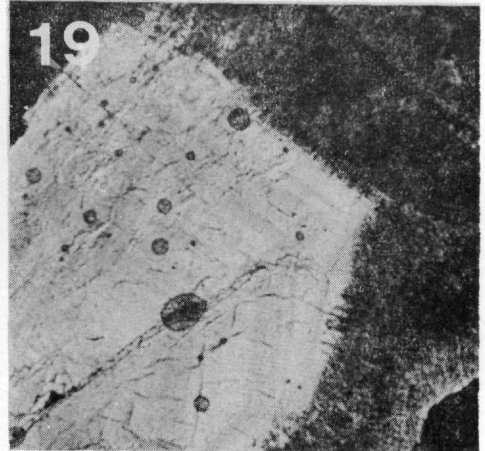
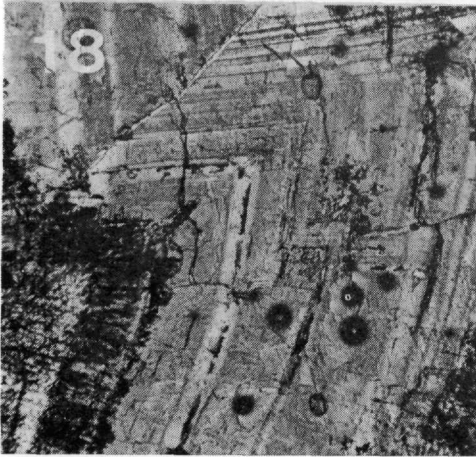
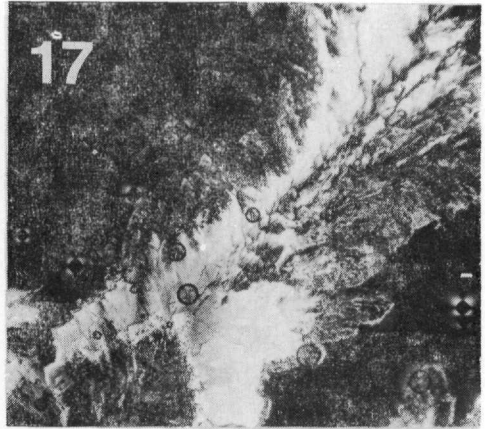
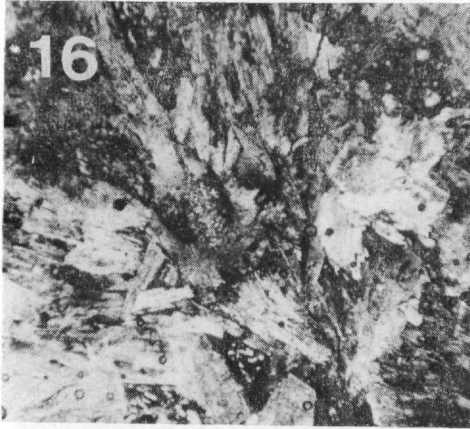


FIGURE 16. Thin section, crossed nicols. Randomly oriented, matted aggregate of barite crystals. ( $\times 25$ )

FIGURE 17. Thin section, crossed nicols. Plumose structure of barite. Note the numerous, frond-like crystal units. ( $\times 25$ )

FIGURE 18. Thin section, crossed nicols. Barite. Note chevron-strip zoning. ( $\times 60$ ).

FIGURE 19. Thin section, crossed nicols. White opaque zones of barite. Note parallelism of opaque zones. ( $\times 25$ )

nately in the mineral zone, whereas colorless and white celestite crystals occurred in the quarry wall below the mineral zone.

*Relation to Host Rock.* Examination of thin sections of celestite crystals and the associated matrix rock showed no evidence of any replacement between dolomite and celestite. Celestite commonly occurs as euhedral crystals, and is not generally found as interstitial pore-filling material in the dolostone. The interface between celestite crystals and dolostone is sharp and no dolomite

rhombs were included in the basal portions of the celestite crystals.

*Habit and Form.* The gray-blue and blue crystals are prismatic to blocky (fig. 20), occurring as well-formed separate individuals as much as 1 cm in maximum dimension. These crystals are simple morphologically. The  $\{100\}$  and  $\{011\}$  forms, with minor modification by  $\{101\}$ , dominate the morphology of nearly all the gray-blue and blue crystals. With generally minimal development,  $\{001\}$  and  $\{210\}$  are present on a few of the crystals. The major pinacoid form,



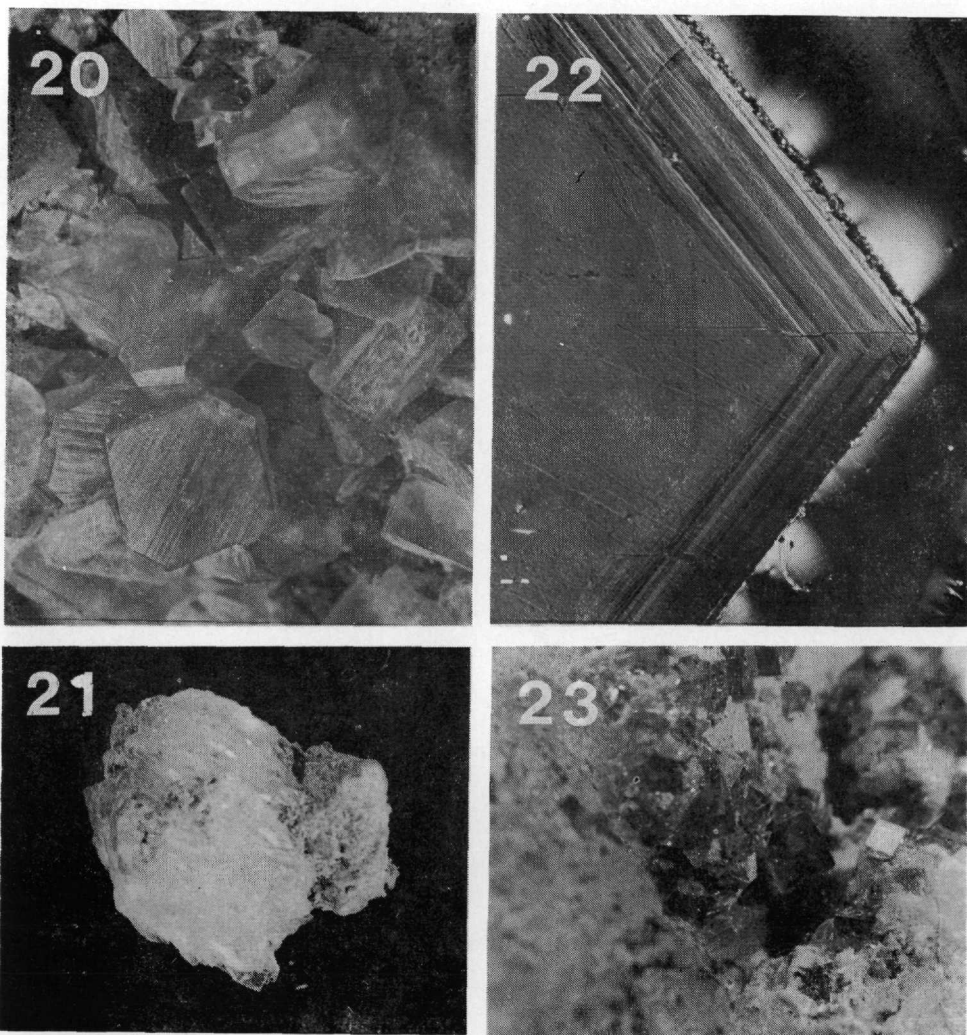


FIGURE 20. Blocky blue celestite on dolostone. Note the striations on the [100] pinacoid, the [101] prism, the [011], and the [001] pinacoid. ( $\times 4.3$ )

FIGURE 21. Celestite on dolostone, colorless to white bladed crystals arranged in a rosette manner. ( $\times 3.4$ )

FIGURE 22. Thin section, crossed nicols. Celestite. Blocky, blue-gray crystal,  $B_{xa}$  orientation. Note the distinct zoning parallel to the [011]. ( $\times 60$ )

FIGURE 23. Celestite, fluorite, and calcite on dolostone. Fluorite is paragenetically earlier than celestite. ( $\times 3.5$ )

{100}, is invariably striated and commonly shows marginal development of {h0 $\ell$ }. The numerical values of the {h0 $\ell$ } form are  $\phi = 90^\circ$  and  $\rho = 84^\circ$ .

The colorless and white crystals are tabular to bladed and occur as distinct individuals and as compact clusters resembling rosettes (fig. 21). The individuals are typically less than 5 mm in maximum dimension, and the rosette-like

clusters are generally about 1 cm in diameter. The major form is the strongly striated {100} pinacoid, but {101} and {011} prism forms are invariably present as well. Several {hk $\ell$ } forms of minimal development were observed on these crystals, but could not be precisely defined.

*Microscopic Features.* Oriented thin sections perpendicular to each of the

three principal axes were prepared from the blue celestite crystals. Narrow light and dark zones were readily observable under low magnification in  $B_{xa}$  sections. These zones were parallel to the  $\{011\}$  form, which is the most prominent form in these crystals (fig. 22). Additional zones were parallel to  $\{011\}$ , the most prominent cleavage direction of celestite. The zones were not readily visible when b and c axes oriented parallel with the axis of the microscope.

Under low magnification with cross nichols, the zones appeared to be 0.005 to 0.01 mm in width. Under high magnifications in plain light, the light and dark zones were resolved into many very fine light and dark bands with a minimum width of 0.001 mm. These fine bands were surprisingly uniform in width and continuity, and are parallel to  $\{011\}$ .

The precise nature of the wide and narrow zones is not known. The fine bands may be similar to the bands described by Roedder (1969) occurring in celestite crystals from Clay Center Quarry, located about 30 miles to the northeast in Clay Center, Ohio. Electron probe analysis for barium and strontium revealed that the light bands contain more Ba than the dark bands; and Roedder concluded that the light and dark bands result from small differences in their indices of reflection caused by the differences in their Ba content, suggesting that annual change in solution

chemistry was the most acceptable explanation for their origin.

*Relationship of Celestite to Other Minerals.* Megascopic and thin section examination of coexisting celestite and calcite crystals indicated that celestite crystals were beginning to form prior to the cessation of calcite crystal growth, and that the greatest amount of celestite formed after cessation of calcite precipitation. No calcite crystals were found perched on celestite. Intergrowths of celestite and calcite were observed only rarely. Fluorite was paragenetically earlier than celestite (fig. 23), but no specimens were obtained which defined the paragenetic relationship between barite and celestite.

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