Geology and mineralization of the Minerva Mine No. 1, Hardin County, Illinois

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GEOLOGY AND MINERALIZATION OF THE MINERVA MINE NO. 1,
HARDIN COUNTY, ILLINOIS

BY
M. P. NACKOWSKI

A
THESIS
submitted to the faculty of the
SCHOOL OF MINES AND METALLURGY OF THE UNIVERSITY OF MISSOURI
in partial fulfillment of the work required for the
Degree of
MASTER OF SCIENCE, GEOLOGY MAJOR
Rolla, Missouri
1949

Approved by
Professor of Geology
ACKNOWLEDGMENTS

I am grateful to the many individuals whose generous aid and cooperation made this study possible. Dr. O. R. Grawe, Chairman of the Geology Department, suggested the problem, supervised it, and critically read the manuscript. Mr. J. H. Steinmesch, Vice President and General Manager of the Minerva Oil Company, granted free access to the Minerva Mine No. 1; made available a base map on which geology of the mine could be plotted, eliminating the necessity of surveying the mine workings; and furnished churn drill hole data from which the vertical geologic section was plotted. Various problems were discussed with Mr. Gill Montgomery, General Superintendent, Minerva Oil Company. Mr. C. W. Shaw, Engineer-Geologist, Minerva Oil Company, acquainted me with the mine workings. I am grateful to Mr. A. H. Cronk, General Superintendent, Rosiclare Lead and Fluorspar Mining Company, for permission granted to visit the mines of this company. Mr. A. G. Johnson, Chief Geologist, Ozark Mahoning Company, gave permission to visit the West Green Mine, and Mr. E. A. Brecke, Geologist, Ozark Mahoning Company, accompanied me through the mine. Mr. D. C. Gibson, Jr., Superintendent, Crystal Fluorspar Company, allowed free access to the Crystal Mine.
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INTRODUCTION

Purpose of investigation:

This study originally was undertaken to describe the witherite identified in specimens collected at the Minerva Oil Company Mine No. 1, Hardin County, Illinois. The original specimens of witherite were collected on October 25, 1948, by Charles E. Tothill, while on a senior trip through the fluor spar mine. The witherite was identified by Dr. O. R. Grawe, Chairman of the Geology Department, Missouri School of Mines, Rolla, Missouri, to whom the specimens were presented. Dr. Grawe suggested that the writer visit the southern Illinois fluor spar area to determine the occurrence and distribution of the witherite. This mineral had been described previously from a limited number of localities in the United States and in the world, but had not been described from the fluor spar district of southern Illinois.

The study was extended to describe the geology and mineralization of the Minerva Mine No. 1. This mine is the most recently developed producing fluor spar mine in the Cave in Rock district of southern Illinois.

Conditions under which the work was done:

Field work was completed during 15 days which were spent in the Hardin County area. The first trip to the fluor spar district was taken from December 26, 1948, to
January 3, 1949. During this period, the drift level geology of the Minerva Mine No. 1 was mapped, and samples for laboratory study were collected. From April 8, 1949, to April 13, 1949, other mining properties in the Cave in Rock area, Hardin County, Illinois, were visited. The geology and mineralogy of these mines were compared with that of the Minerva Mine No. 1. From May 31, 1949, to June 5, 1949, surface expression of geologic structures observed in the Minerva Mine No. 1 workings were sought.

Laboratory study was conducted in the Geology Department, Missouri School of Mines, Rolla, Missouri. Rock and mineral specimens collected were studied megascopically and microscopically. X-ray diffraction patterns of unknown minerals were run. In addition, qualitative chemical methods of analysis were employed where necessary for the identification of mineral species.

Summary of previous work:

Numerous descriptions of the occurrence of fluorspar in the Illinois-Kentucky fluorspar district have been published. Extensive geological studies also have been completed.

The earliest published description of the occurrence of fluorite in the Illinois fluorspar district appeared as notices in the first, second, and third volumes of the American Journal of Science, published in 1818, 1820, and 1821.

In 1819, Schoolcraft described the occurrence of "fluate of lime" near Cave in Rock, Illinois. The "fluate of lime" was found in abandoned diggings embedded in a stiff red clay. A second description by Schoolcraft referred to the "fluate of lime" as the "detritus of pre-existing veins".

This was followed in 1852 by Brush's description of a fluor spar occurrence in Gallatin County, Illinois.


(5) Worthen, in 1866, described fluor spar vein occurrences in

Hardin County, and Emmons, in 1893, described the occurrence of vein fluor spar near Rosiclare, Illinois. E. O.


(7) Ulrich and Tangier Smith, in 1905, included an historical


summary of described fluor spar occurrences in southern Illinois and Kentucky in their report on the Kentucky deposits. In 1904, Bain wrote a brief note concerning the


vein fluor spar deposits in the Kentucky-Illinois district, and a year later, he described the geology of the fluor-


spar deposits of southern Illinois in greater detail. He called attention to the bedded or sheet deposit of fluor spar at the Lead Hill Mine, in the Cave in Rock district and
concluded that the fluorine was introduced along horizontal bedding planes and metasomatically replaced the calcite in the Fredonia limestone beneath the Rosiclare sandstone.

(10) In 1920, Weller, in collaboration with Butts,

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Currier, and Salisbury, published the Geology of Hardin County, the economic geology involving the fluorspar, lead, and zinc in Hardin County being treated by Currier and Butts. The geology of the vein deposits, bedding replacement deposits, and residual deposits was described.

(11) Spurr, in 1926, considered genetic problems of the Illinois-Kentucky fluorspar vein and bedding replacement deposits. In 1928, Schwerin described the bedding replacement fluorspar deposit adjacent to the Spar Mountain Mining Company property in the Cave in Rock area, and

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Bastin, in 1931, described the vein and bedding replacement fluorspar deposits and suggested that the banded or "coon-tail" ore was the expression of diffusion banding.

Currier, in 1935, discussed the structural setting of the fluorspar deposits and took exception to Bastin's theory of "diffusion banding" for the development of the "coon-tail" ore. In 1937, Currier attributed the formation of this banded ore to replacement of limestone by fluorite with the preservation of the bedding and cross-bedding of the rock.

The field investigations by Currier with the collabora-

---


tion of O. E. Wagner, Jr., carried out in 1934 and 1935, were published in detail in 1944. This is the most recent publication concerning the fluorspar deposits under consideration.
LOCATION AND ACCESSIBILITY

The Minerva Oil Company Mine No. 1 is located in the SE1/4 of Section 24, T11S, R9E, five miles north of Cave in Rock, Hardin County, Illinois. The location of the mine is shown on Figure 1. The mine is one mile east of Illinois highway No. 1, a black topped north-south artery. The Minerva Oil Company has 3,000 acres of land in this vicinity. Previously known bedding replacement fluorite occurrences which characterize the Cave in Rock district of the Illinois-Kentucky fluorspar area, and which have been described by Currier, are located southwest of the landholdings acquired by the Minerva Oil Company.


EXPLORATION AND DEVELOPMENT

J. H. Steinmesch, following Currier's idea of the dependency of fluorspar mineralization to northeasterly trending fractures, inaugurated an exploratory churn drilling program by the Minerva Oil Company in 1939 to extend the apparent northeasterly trend of the known Cave in Rock bedding replacement deposits. By 1942, more than one

FIGURE 1, LOCATION MAP, HARDIN COUNTY, ILLINOIS
hundred holes had been drilled, and a deposit of 311,000 tons containing 5.47% zinc and 37.1% fluorspar and 219,000 tons containing 3.33% zinc and 20.53% fluorspar was outlined. A mineralized zone was intersected in the Renault formation of Chester age and another in the underlying Levias and Fredonia members of the Ste. Genevieve formation.

Following the exploration program, development work was undertaken. A shaft, sunk to a depth of 645 feet was completed in 1943. From this shaft, haulage drifts were driven and ore passes were completed to the ore horizon. A 250 ton selective flotation mill was constructed to produce zinc and fluorspar concentrates and by March, 1944, the mine was in daily production. A room and pillar method of ore extraction is employed.
DESCRIPTIVE GEOLOGY

GENERAL STRATIGRAPHY

In the Cave in Rock district, the rocks exposed at the surface are sediments of Mississippian and Pennsylvanian age. The strata strike approximately N.70° W. and dip homoclinaly to the northeast. The average dip ranges from 3° - 5°.

The oldest formation exposed in the Cave in Rock district, here defined as including all of Hardin County east of the Peters Creek faults, is the Fredonia limestone of Mississippian age. The youngest formation which outcrops in the northern portion of the Cave in Rock district is the Caseyville conglomerate of Pennsylvanian age.

The stratigraphy of the Minerva Oil Company Mine No. 1 was obtained from churn drill hole records. The formations intersected by the drill holes are shown in Figure 2.

In the vicinity of the Minerva Mine No. 1, the Tar Springs sandstone and the overlying Menard limestone, both of Mississippian age, underlie the surface soil. The shaft of the Minerva Mine is bottomed in the Levias limestone, which is of upper Ste. Genevieve, Meramec age. The drift level workings are in the Levias limestone and in the over-
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Compiled from Minerva Oil Company Churn Drill Hole Data

FIG. 2 COLUMNAR SECTION MINERVA MINE
lying Renault formation, which is of lower Chester age. Stoping is confined to the mineralized Downey's Bluff, which is the upper member of the Renault formation.


DETAILED STRATIGRAPHY

MISSISSIPPIAN SYSTEM

Meramec Series

Ste. Genevieve Formation

The Ste. Genevieve formation is composed of three successive members, which from oldest to youngest are: the Fredonia limestone, the Rosiclare sandstone, and the Levia limestone.

Fredonia limestone:

The base of the Fredonia limestone was not encountered in the drill holes studied. The Sub-Rosiclare sandstone is the lowest zone of the Fredonia limestone intersected in churn drill holes. It occurs 60 feet below the top of the Fredonia limestone and is 10 feet thick. The Sub-Rosiclare sandstone has been described by Wagner as being markedly

cross-bedded and extremely porous, where exposed, because of the leaching of the calcareous material by weathering. In 1945, Tippie proposed the name of Spar Mountain sandstone to replace the name Sub-Rosiclare sandstone.

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The upper 60 feet of the Fredonia were intersected by a churn drill hole in the vicinity of the Minerva Mine. The limestone is gray, fine-grained to dense, and oolitic.

Rosiclare sandstone:

The Rosiclare sandstone intersected in churn drill holes on the Minerva Oil Company property varies 20 to 40 feet in thickness. Predominantly it is a fine-grained and light gray calcareous sandstone, but the basal portion, immediately overlying the Fredonia limestone, is a dark green to gray shale, 6 to 12 inches thick. To Wagner, the Rosiclare sandstone appeared to be conformable with the underlying Fredonia limestone, but Tippie, who examined

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diamond drill cores obtained in exploratory drilling for fluor spar in Hardin County, Illinois, and in Kentucky, concluded that an unconformity exists between the Rosiclare sandstone and the underlying Fredonia limestone. He showed that the erosional unconformity is angular, the erosion having been accompanied by pre-Rosiclare warping.

On the basis of similar evidence obtained previously in the Illinois Basin, Workman proposed that the base of the Rosiclare sandstone be considered the base of the Chester series. Swann in 1948 correlated the Rosiclare sandstone with the Aux Vases sandstone of adjoining regions. If the Aux Vases sandstone is to be considered basal Chester in this region, then the Rosiclare sandstone is basal Chester also.

Leviias limestone:

The Leviias limestone, youngest member of the Ste. Gene-


vieve formation, is 20 to 60 feet thick and is similar in
texture to the Fredonia limestone. It is gray and varies
from oolitic through fine-grained to dense.

(27) The name Levias was proposed to replace Weller's

(27) Sutton, A. H. and Weller, J. M., "Lower Chester Corre-
lation in Western Kentucky and Illinois", Jour. Geol.,


"Lower O'Hara". Weller considered the contact between


the "Lower O'Hara" and the underlying Rosiclare sandstone to
be conformable. He considered the upper contact between the
"Lower O'Hara" and the Chester series to be unconformable.
According to Weller, the unconformable surface everywhere
"is marked by a distinct basal conglomerate."

Chester Series
Renault Formation

(30) The Renault formation encountered in drill holes on

(30) Weller, Stuart, Kentucky Geol. Sur., Ser. 6, Vol. 4,
pp 27-30, 1921.
the Minerva property may be subdivided on a lithologic basis into two members; the basal Shetlerville shale, and the overlying "Renault limestone" or Downey's Bluff member. The thickness of the formation varies from 30 to 70 feet.

Shetlerville shale:

The Shetlerville shale is an interbedded shale and limestone sequence 10 to 35 feet thick. The shale is dark green to gray thin-bedded, and in part, fissile. The interbedded limestone is dense to fine-grained, and in part, crinoidal. The layers of limestone and shale grade laterally into one another. The thickest individual shale bed measured in the Minerva Mine was 8 feet thick. The limestone layers are from 2 inches to 4 feet thick.

In 1943, Tippie zoned the Renault formation on the basis of insoluble residues obtained from diamond drill cores and from outcrop samples. The zones were designated A, B, C, D, and E, starting at the base of the formation. In the Minerva Mine, the lower predominantly shale portion of the Renault formation was considered to comprise the Shetlerville shale member.

Downey's Bluff, or "Renault limestone":

The upper member of the Renault formation is the so-called "Renault limestone" or Downey's Bluff. 20 to 35 feet of this limestone were out by the drill holes. The limestone is gray to brown, thick-bedded, and varies texturally from dense to medium-grained. Oolitic and crinoidal beds are present. The "Renault limestone" has been named the Downey's Bluff member by Tippie from the type locality (32).


Downey's Bluff along the Ohio River bluff at Rosiclare. In this report the name "Renault limestone" is retained because it is the name in common usage in the Illinois fluor spar field.

In the Minerva Mine workings, the upper parts of the "Renault limestone" are porous. This porosity may have been induced by subaerial weathering or by solution by circulating ground water, or by both. The "Renault limestone" is overlain unconformably (33)(34).


by the Bethel sandstone. Tippie found that the Bethel sandstone, in the Illinois fluor spar area, rests in places directly on Zone C and D of the Renault formation. The absence of the overlying zones indicates an unconformity between the Renault formation and the overlying Bethel sandstone.

Bethel Sandstone

Weller found that the Bethel sandstone varies in thickness from 45 to 100 feet. It is composed of subrounded well-sorted quartz sand and a very little feldspar and zircon. The sandstone is compact and is cemented by quartz. It is tan to nearly white and when fresh, is cross-bedded and ripple-marked. The Bethel sandstone is separated from the Renault limestone by a shale layer which is usually 6 to 12 inches thick, although locally it may be 2 to 3 feet thick. The Bethel sandstone is the youngest formation exposed in the stopes of the Minerva Mine.

In the vicinity of this mine, it is overlain directly by the Cypress sandstone. The Paint Creek shale, which normally separates these two formations, is missing.

The following described formations successively overlie the Bethel sandstone and are described only briefly because they are not directly related to the fluor spar deposits.
Cypress Sandstone

The combined thickness of the Cypress sandstone and Bethel sandstone, as obtained from churn drill data, ranges from 170 to 200 feet. The Cypress sandstone is similar to the Bethel sandstone in character.

Colconda Formation

The Colconda formation is 160 to 180 feet thick in the vicinity of the Minerva Mine. It is composed of a succession of shale and limestone beds, but is predominantly limestone.

Hardinsburg Sandstone

Churn drill data indicates that the Hardinsburg sandstone ranges from 70 to 90 feet in thickness. The Hardinsburg sandstone contains shale beds and shaly partings; therefore it is not as massive as the underlying Cypress and Bethel sandstones.

Glen Dean Limestone

The Glen Dean limestone varies in thickness from 60 to 75 feet. The formation is comprised of alternating shale and limestone beds.

Tar Springs Sandstone

The Tar Springs sandstone is 60 feet thick. It is tan to nearly white. Interbedded shale is present. The Tar Springs sandstone forms the bedrock over part of the area in the vicinity of the Minerva Mine.
Menard Limestone

The Menard limestone also underlies the surface in the vicinity of the Minerva Mine. A maximum thickness of 20 (36) feet was encountered in the drill holes. Weller determined its regional thickness as 80 to 120 feet. The Menard is predominantly comprised of limestone beds, although some shaly partings are present. It is overlain unconformably to the northeast of the Minerva Mine by the Caseyville conglomerate of Pennsylvanian age.

GEOLOGIC STRUCTURE

Folds

The Cave in Rook district is on the northeast limb of a broad domal structure which trends northwesterly, through the Illinois-Kentucky fluor spar area. The sedimentary rocks of this region strike N.70°W. to N.80°W. and dip homoclinally to the northeast. At the southern end of the Cave in Rock district, near the crest of the fold, the average dip is 2°. The dip steepens gradually to the northeast on the flanks of the fold. In the vicinity of the Minerva Mine, the average dip is from 5° to 5°.

Local variations in strike and dip were noted in the Minerva Mine workings. These variations are related to the fracture system present. Minor anticlines and synclines within fracture zones trend parallel to the strike of the fractures.

Drag of beds along faults also was noted in the mine workings. The steep dips are due to drag restricted to the immediate vicinity of the minor faults. The steepest dip observed was 45°. The strikes of the dragged beds parallel the fractures to which they are related.

Fractures

A large number of normal faults are associated with the broad domal structure which characterizes the Illinois-Kentucky fluor spar area. These faults have vertical displacements up to 1500 feet.
In Hardin County, the predominant faults strike N.25°E. to N.55°E., and are steeply dipping, or vertical. Both northwesterly and southeasterly dipping faults are present.

The Cave in Rock district is bounded on the west by the Peters Creek fault zone, which strikes N.50°E. and has an overall displacement of 1000 feet downthrown on the northwest side. None of the major normal faults which characterize the Illinois-Kentucky fluorspar area occurs within the Cave in Rock district itself.

In the vicinity of the Minerva Mine, exposures of fractures can be found in creek bottoms. The fracture pattern developed consists of three sets of nearly vertical fractures. One set strikes N.50°E. to N.55°E. paralleling the trend of the prominent normal faults. The second set strikes N.55°W. to N.35°W., and the third set strikes east-west.

This same fracture system is present in the underground workings of the Minerva Mine, as shown in Figure 3. The few normal faults present strike N.50°E. to N.55°E. The maximum measured vertical displacement along one of these faults is


Note: Stope are within the Downey's Bluff, and slope downward toward the northeast. Dotted lines indicate stopes above drift level.
3 feet. The majority of the fractures of this set are joints. The fractures which trend N.55°W. to N.60°W. and those which trend east-west are also joints, since no perceptible displacement is present along them. In the mine workings the fractures are filled with calcite and with calcite and fluorite, forming veinlets which range in width from 1/16 of an inch to 4 inches. The majority of the veinlets are from 1/2 to 1 inch wide.

The character of the fractures is controlled by the structural competency of the formations through which they pass. This control is more noticeable with the smaller joints. The larger fractures pass through the limestone, shale, and sandstone sequence without deviation in their course, while the smaller fractures are most closely spaced in the shales and are widely spaced in the sandstones. The spacing of the fractures in the limestone is intermediate. Some of the joints within the shales are discontinuous. Joints passing from limestone into shale may end within the shale bed. Bedding plane slipping within the shale beds has displaced some of the fractures. In the massive limestone, the joints are continuous and consistent in their dip. In the bedded limestone, however, the smaller joints are step-like in character. A vertical joint will change direction of dip, follow a bedding plane for a distance of 1 to 24 inches and then continue vertically. The step-like pattern is repeated by the smaller joints which traverse the bedded
The N.50° E. to N.55° E. set of fractures are predominant in the Cave in Rock district and in the workings of the Minerva Mine. Within the mine, they occur in zones which coincide in position with the mineralized zones, as shown by the relation of the stopes to the fractures on the mine map Figure 3, and on the Geologic Cross Section, Figure 4. The east stope fracture zone, 200 feet wide, consists of a series of closely spaced N.50° E. trending fractures. The drift level mine workings between the east and west stopes, a distance of 600 feet, are traversed by occasional minor fractures. The west stope fracture zone, 150 feet wide, contains a closely spaced fracture pattern similar to that of the east stope. Two hundred feet northwest of the west stope, No. 3 stope also occurs in a similar fracture zone. The fractures were developed both prior to and contemporaneous with mineralization. Pre-mineral fractures are filled with vein material. Inter-mineral fracturing is indicated by vein filling or "healing" of fractured calcite veins.
FIGURE 4. GEOLOGIC VERTICAL SECTION, MINERVA MINE NO. 1

Section Projected to Line A - A', Figure 3
MINERALIZATION

The minerals associated with the fluorspar of the Minerva Mine include most of those previously described from other mines in Hardin County, Illinois, and in


addition, two minerals, witherite and strontianite, which have not been described previously from the area. Witherite and strontianite were identified in specimens from the Minerva Mine No. 1. Witherite also was found in the West Green Mine of the Ozark Mahoning Company. Marcasite,


which has been described previously in specimens from the bedding replacement deposits was not observed by the present writer.

Description of Minerals

Calcite:
Calcite deposited from mineralizing solutions is present in the ore bodies and as veinlets filling fractures. It is colorless, white, yellowish, or gray, and is fine-
grained to coarse-grained. The vein calcite has poorly developed crystal faces. The calcite deposited in open spaces occurs as singly or doubly terminated scalenohedrons which are modified by rhombohedral faces. Coarsely crystalline gray calcite has filled cavities in the ore. These rhombohedral calcite masses are from 6 to 24 inches long. Crusts of white fine-grained, powdery calcite coat the walls of open channels.

Fluorite:

Fluorite is the most abundant useful mineral in the Minerva Mine. Its grain size varies from microscopic to crystals which measure 4 inches on edge. The fluorite is poorly crystallized where it occurs as disseminated grains in the limestone, and well-crystallized where it has been deposited in open cavities. The most common form is the cube. Octahedral faces rarely modify the cube form.

The fluorite is white, yellowish buff, greenish blue, sky blue, lavender, and purple. Individual crystals commonly show color zoning, which gives rise to ghost crystals. The color boundaries are sharp, although a gradation in intensity of a color may occur within a particular zone.

Inclusions are present in the fluorite. When abundant, the inclusions are symmetrically arranged according to a cubic pattern because they were deposited on exposed cube crystal faces. Continued growth of the fluorite crystals enclosed the foreign matter. The inclusions recognized in
the fluorite crystals from the Minerva Mine consisted of chalcopyrite. Hydrocarbon inclusions have been reported


from other mines in the fluorite district.

**Barite:**

The barite in the Minerva Mine is granular, powdery, acicular, or tabular. It is white, yellowish, or colorless. The tabular crystals have a well-developed equidimensional basal pinacoid, a narrow prism, and small macro- and brachydomes. The barite was deposited primarily in open channels and in adjoining cavities.

**Witherite:**

The witherite occurs as pseudo-hexagonal twinned crystals and aggregates. The pseudo-hexagonal twins are stubby and columnar. Nearly flat dipyramidal faces terminate the columns. The witherite is white to buff, waxy to vitreous, and occasionally zoned. Some pseudo-hexagonal crystals have a white waxy core surrounded by a buff vitreous exterior. Inclusions are present in some specimens along the zone boundary.

The small witherite twins are multiple cyclic twins with the unit prism acting as the twinning plane. In the
larger twins, a complex arrangement of individuals occurs. Cyclic twinning still is developed with the unit prism as the twinning plane, but polysynthetic twinning according to the same law also is present, as shown in Figure 5. In addition, the twins exhibit an aggregate texture which is best observed in thin sections under crossed nicols. Frequently this aggregation gives rise to a radial or even flamboyant effect.

Under an ultraviolet lamp, the witherite strongly fluoresces white. A weak yellow phosphorescence is also exhibited. The x-ray diffraction pattern obtained from witherite from the Minerva Mine was identical with that obtained from English witherite.

Witherite was deposited in open cavities and channels exclusively. At the West Green Mine, the witherite is corroded, having undergone partial zonal solution by groundwater.

Strontianite:

Strontianite was identified in specimens from the Minerva Mine by the writer. It is pink to brown, and bladed to acicular. The brown color is due to petroleum inclusions in the acicular aggregates of the mineral. Physical, optical, and chemical tests were supplemented by an x-ray diffraction pattern in the identification of the strontianite.
GENERALIZED CAMERA LUCIDA SKETCH OF ONE HALF OF A SIMPLE PSEUDO-HEXAGONAL TWIN AS SEEN IN THIN SECTION ORIENTED PERPENDICULAR TO THE "C" AXIS UNDER CROSSED NICOLS. (EX)

SCHEMATIC DIAGRAM OF THE WITHERITE TWIN. TWIN PLANE (110). DOTTED LINE INDICATES DIRECTION OF THE "A" AXIS.

FIG. 5, SKETCH AND DIAGRAM OF SIMPLE PSEUDO-HEXAGONAL WITHERITE TWIN.
Although strontianite has not been described previously from Illinois fluor spar mines, celestite has been described from the Jameson prospect, eight miles northwest of Salem, Livingston County, Kentucky.

Quartz:

Colorless quartz crystals are present in the Minerva Mine. The quartz crystals vary from 1/8 to 1/4 of an inch in length, and exhibit horizontally striated hexagonal prism faces and rhombohedral faces. The quartz has formed on other minerals.

Sphalerite:

Sphalerite, honey yellow or dark brown, is widely distributed. The grains range from microscopic dimensions to crystals which are 1/2 to 3/4 inches across.

Chalcopyrite:

Chalcopyrite is not abundant in the Minerva Mine, but it is widely distributed. The simple tetragonal diaphenocid (111) is the crystal form developed. The chalcopyrite occurs as inclusions within the fluorite, and is also attached to crystal faces of the fluorite and other minerals.
Galena:

Galena is not common in the workings of the Minerva Mine. Crystal aggregates were observed. The crystals were cubes modified by octahedrons.

Petroleum:

Petroleum seeps occur in the mine workings along fractures and bedding planes. The sandstones and limestones of the Chester series yield oil commercially in southern Illinois.
**Paragenesis of the Fluorspar Deposit**

The sequence of mineral deposition in the Minerva Mine is similar to that noted by Bastin.


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**Fluorite:**

The first mineral to be deposited was fluorite, and this mineral continued to be deposited throughout the major portion of the period of mineralization. Leached cupsp-like surfaces of fluorite were seen along open bedding plane channels, indicating a period of fluorite solution.

Small crystals of fluorite $1/16$ to $1/8$ of an inch across are found deposited on witherite surfaces, indicating that at least a minor amount of fluorite was deposited after the crystallization of the witherite.

**Sphalerite:**

Cross-cutting relationships were not noted between fluorite and sphalerite. In thin section, fluorite crystals euhedral to sphalerite or enclosing sphalerite were observed. These observations indicate that sphalerite crystallized after the first fluorite had been deposited and ceased before the deposition of fluorite was complete.

**Chalcopyrite:**

Chalcopyrite occurs as zonally distributed inclusions in fluorite. The chalcopyrite was deposited on the cube
faces of the fluorite, which with continued growth enclosed the chalcopyrite. Chalcopyrite also occurs as disphenoid crystals on witherite. This indicates that chalcopyrite continued to be deposited after the formation of the witherite. Chalcopyrite deposition began after fluorite, and continued throughout the period of mineralization.

**Galena:**

The limited occurrence of galena in the Minerva Mine prevented a precise determination of its age. It occurs as crystals on fluorite and is later than the fluorite. In the Crystal Mine, galena crystals were found coated with a thin film of chalcopyrite, indicating that it is older than the chalcopyrite.

**Calcite:**

Calcite veinlets cross-cut fluorite. This indicates fracturing of the fluorite and subsequent sealing of the fractures by calcite. These calcite veinlets occur as a netlike box-work in open channels along which fluorite has undergone solution. Small calcite crystals found on witherite indicate that the deposition of calcite continued after the witherite was formed. Crusts of powdery calcite on other minerals were noted and may have been deposited from ground water after cessation of mineralization.

**Barite:**

Some of the barite is partly replaced by witherite. Acicular aggregates of barite have been infiltrated by
strontianite, which partly replaces the barite. The distribution of barite is related to the open channels and cavities. No barite was noted on leached remnants of fluorite, however, indicating that it was deposited prior to the solution of fluorite.

Witherite:

Partly replaced barite rods are enclosed in the pseudo-hexagonal witherite twins. Witherite was also found in cavities of acicular aggregates of barite. The witherite is principally related to open bedding plane channels and cavities. It is found crystallized on or along calcite veinlets, which have remained as a box-work, following the solution of fluorite through which these veinlets originally cut. Witherite therefore was deposited after the period of fluorite solution.

Strontianite:

Strontianite fills open spaces in masses of loosely aggregated barite needles. Strontianite has partly replaced barite needles, indicating that it was deposited after barite.

Quartz:

A small amount of quartz is present in the Minerva Mine. Quartz crystals were deposited on crystal faces of fluorite, calcite, barite, and witherite, indicating that its deposition outlasted that of the other minerals. Powdery crusts of calcite, however, do coat the quartz crystals.
NATURE OF THE FLUORSPAR DEPOSIT

Ore Textures

The ore in the Minerva Mine can be separated texturally into three classes which are genetically related to the physical-chemical conditions prevailing during the period of mineralization and to the physical characteristics of the host rock. The physical-chemical conditions involve primarily temperature, pressure, absolute and relative concentrations of ions and molecules in solution, and changes in these factors during the period of mineralization.

Banded, or "coon-tail" ore:

The banded ore is composed of alternating layers of light-colored and dark-colored fluorite, or alternating layers of pure fluorite and impure fluorite. Each layer or band is from 1/2 to 2 inches thick. These layers extend parallel to the bedding of the host rock and according to Currier, "reflect and preserve the original bedding."


cross-bedding, and to some extent, the textures of the host limestone". (45)

Bastin has attributed the banding to deposition of fluorite by rhythmic precipitation during replacement of the

limestone by diffusing mineralizing solutions. The banding was found not to be parallel to the bedding in all cases. Where departures from parallelism were marked, the orientation of the banding was related to small fractures cutting across the bedding planes.

The banded or "coon-tail" ore is developed to a limited extent at the Minerva Mine No. 1. The banding reflects the structure of the replaced limestone, but replacement of carbonate ions by fluoride ions alone cannot account for the structure. Such a reaction would involve a volume change of about 33 percent, for which there is no evidence. Apparently the mineralizing solutions carried calcium fluoride and a volume rather than molecular replacement took place. This also is evidenced by the development of highly crystalline and rather pure fluorite bands between those which exhibit evidence of replacement.

Coarse granular, or massive ore:

The coarse granular ore shows a crude irregular coarse banding in places. The crude bands are from 1 to 4 inches thick. The crystals developed are from 1/2 to 6 inches across. Coarse granular ore fills former cavities and channels. The coarse fluorite includes limestone fragments. The fragments of unreplaced limestone are either parallel to the original bedding of the limestone or assume inclined positions, indicating that they slumped into cavities formed during the period of mineralization.
The growth of comparatively large crystals of fluorite, the indistinct or crude preservation of bedding features, the presence of slump structures and open channels and cavities, indicate that although deposition of fluorite was initiated by replacement of the limestone, the solution of the limestone progressed independently, and the openings formed were filled or partly filled by fluorite deposited from solutions not as concentrated in calcium and fluorine, as were those which developed the banded ore.

**Disseminated ore:**

The majority of the ore in the Minerva Mine is characterized by the presence of fine granular fluorite distributed through the host rock. A linear arrangement of the fluorite grains parallel to bedding of the limestone is visible. Development of disseminated texture is the result of replacement of calcite by fluorite.

**Shape of the Ore Bodies**

The ore bodies of the Minerva Mine are tabular in form and are elongated in a N.50°E. to N.55°E. direction parallel to the strike of the predominant fractures. The ore bodies being mined lie within the "Renault limestone" Downey's Bluff member of the Renault formation. Their upper contact coincides with the basal shale of the overlying Bethel sandstone. Although some disseminated mineralization does occur in the Bethel sandstone, it is not of commercial importance.
The widths of the ore bodies are limited by decreased intensity of mineralization at the outward limits of the fracture zones and range from 50 to 300 feet. The bottoms of the ore bodies are irregular, and not sharply defined. The ore bodies range from 3 to 20 feet in thickness. Their average thickness is 9 feet. The minimum fluor spar and zinc content upon which the limits of the ore bodies are based were not available to the writer.

Relation to Formations

The most important fluor spar-bearing rock in the Cave in Rock district has been the Fredonia limestone of the Ste. Genevieve formation. Several mineralized horizons occur within the Fredonia limestone. The most important and extensive ore bodies lie directly beneath the thin shale found at the base of the overlying Rosiclare sandstone member. A second mineralized horizon has been found directly beneath the Sub-Rosiclare sandstone, which is within the Fredonia limestone, and about 60 feet below the top of this member. Other mineralized horizons of more limited extent also have been found within the Fredonia limestone. These occur directly beneath dense lenses or layers of Fredonia limestone.

Exploratory churn drilling in the Minerva Mine area disclosed mineralization at two new horizons, the "Renault limestone" or Downey's Bluff, and the Levia limestone. Fluorspar had not been produced previously from these stratigraphic zones. Of these, the productive and most inten-
sively mineralized horizon at the Minerva Mine is within the "Renault limestone" Downey's Bluff member of the Renault formation. The ore in this horizon lies directly beneath the thin basal shale of the overlying Bethel sandstone. The upper part of the Fredonia limestone, directly beneath the basal shale of the Nosisclare sandstone also is mineralized, but not worked at present. The mineral occurrence in the Fredonia limestone and in the "Renault limestone" are quite similar, in that both occur beneath a thin shale, which is a basal phase over an overlying sandstone.

Relation to Fractures

The fractures in the Minerva Mine drift level workings can be divided into three sets. One set strikes N.50°E. to N.55°E., the second set strikes N.55°W. to N.60°W., and the third set strikes east-west. All are steeply dipping or vertical. The most prominent fracture set trends N.50°E. to N.55°E. The fractures of this set are grouped in well-defined zones. The mineralized areas occupy positions within the fracture zones trending N.50°E. to N.55°E. In other mines in the Cave in Rock district, the major mineralized trends extend laterally parallel to these same fractures. In addition, ore bodies have been found which have a N.55°W. to N.60°W. trend and are parallel to fractures striking in this direction. Replacement of limestone layers by fluorite adjacent to the fractures is absent except at mineralized horizons.
Relation to Folds

Minor flexures and drag folds are associated with fractures in the Minerva Mine. No marked relationship was noted between these flexures and the intensity of mineralization. In other mines in the Cave in Rock district, Currier has found that mineralization is most intense on flanks of sharp folds, and principally in synclinal troughs. Where ore has been found on anticlinal crests, the folds are sharper than where they are not mineralized.

(47) Currier, L. W. and Wagner, Jr., O. E., op. cit. p. 41.
ORIGIN OF ORES AND FACTORS

CONTROLLING MINERAL LOCALIZATION

The origin of the fluorspar ores of the Illinois-Kentucky fluor spar district has been attributed to deposition of minerals from ascending hydrothermal solutions derived from an underlying differentiated magma. The presence of such a differentiated magma is indicated by the acidic igneous breccia plugs and lamprophyric dikes which occur in the area. That the mineralizing solutions were ascending from below is suggested by the position of mineralized horizons directly beneath impervious cap rocks. The ascending mineralizing solutions travelled along available channels, which were the fractures occurring in this district.

The elongation of ore bodies parallel to the N.50°E. to N.55°E. fracture set indicates they were the more favorable channels of ascent for solutions. Near Rosiclare, Hardin County, the larger faults offered channel-ways of unrestricted movement to migrating solutions. Here are formed the vein deposits, with no related bedding replacement deposits.

In the Cave in Rock area, large fractures have not been encountered. Relief of stresses by fracturing was accomplished in zones of minor normal faults and joints, rather than along a definite plane of major movement. These minor fractures offered restricted channel-ways to ascending mineralizing solutions. Lateral migration of the mineralizing solutions to form the bedding replacement de-
posit has previously been attributed to the damming of the solutions by a cap rock, thereby causing them to spread laterally.


Data obtained in the Minerva Mine workings and from churn drill holes indicate that the damming influence of a cap rock was of secondary importance in mineral localization.

Ascending solutions may be caused to migrate laterally 1) when their ascent is impeded by a dense cap rock at which a fracture is cut off or narrowed, or 2) when the solutions encounter a more permeable channel or medium than that through which they were migrating, or 3) when a combination of the first two factors takes place.

Evidence obtained in the Minerva Mine indicates that the permeable nature of the "Renault limestone" or Downey's Bluff member caused solutions to migrate laterally, although it is overlain by a shale which is only 6 to 12 inches thick. "Renault limestone" specimens obtained from the Minerva Mine within 4 feet of its contact with the overlying Bethel sandstone were porous. It is supposed that this porosity was induced by subaerial weathering, and by solution due to percolating ground waters obtained from the overlying sandstone.
The similar stratigraphic position of the Fredonia limestone, which also is strongly mineralized, with respect to the overlying Rosiclere sandstone gives credence to this postulate.

The second mineralized horizon in the Minerva Mine is within the Levias limestone. Levias mineralization is limited in extent and weak. However, this limestone is lithologically similar to the Fredonia limestone and is overlain by the Shetlerville shale, which contains a shale bed 8 feet thick in the Minerva Mine. If the effect of an impervious cap rock were the primary cause for lateral migration of solutions, the Levias limestone should be at least as strongly mineralized as the Fredonia, with which it is lithologically similar. Therefore, it is concluded that permeability of the "Renault limestone" and the Fredonia limestone was of primary importance in mineral localization, and the presence of an impervious cap rock was of secondary importance.
CHEMISTRY OF THE FLUORSPAR DEPOSIT

Various theories have been proposed to describe the chemistry of fluor spar deposition. Weller proposed the following reactions assuming that fluorine and silica were solutes, and that fluorine was obtained from an underlying differentiated magma.

1) \[2F_2 + 2H_2O \rightarrow 4HF + O_2\]
2) \[SiO_2 + 4HF \rightarrow SiF_4 + 2H_2O\]
3) \[SiF_4 + 2CaCO_3 \rightarrow SiO_2 + 2CaF_2 + 2CO_2\]
4) \[2HF + CaCO_3 \rightarrow CaF_2 + H_2O + CO_2\]

The presence of elemental fluorine indicated in reaction 1 as a magmatic differentiate, or "fugitive constituent" is questioned. Fluorine is a component of certain igneous and related minerals, indicating that it was present in the magma in the ionic state. Quartz, although present in the fluor spar deposits, does not exist in quantities required if reactions 2 and 3 were largely responsible for fluor spar deposition. It is probable that fluorine in the ionic state was accompanied by sodium, potassium, calcium, or other ions, as well as by hydrogen ions. It is assumed...
that the mineralizing solutions had a low hydrogen ion concentration, thereby limiting the reaction of fluoride ions with silicates to form $\text{H}_2\text{SiF}_6$.

The following generalized equilibrium reactions are presented to illustrate the nature of fluorite deposition:

4) $2\text{HF} + \text{CaCO}_3 \rightleftharpoons \text{CaF}_2 + \text{H}_2\text{CO}_3$

5) $\text{H}_2\text{CO}_3 + \text{CaCO}_3 \rightleftharpoons \text{Ca} \{\text{HCO}_3\}_2$

6) $\text{Ca}^{++} + 2\text{F}^- \rightleftharpoons \text{CaF}_2$

Reaction 4 involves the stoichiometric replacement of calcite by fluorite. The production of carbonic acid by this reaction will result in the solution of limestone as indicated in reaction 5 with the development of the soluble calcium bicarbonate. The increased concentration of calcium ions in solution will force the deposition of further fluorite as indicated in reaction 6. The formation of the bicarbonate ion will also decrease the concentration of $\text{CO}_2$ in solution and so allow reaction 4 to progress further to the right than indicated.

A decrease in the degree of saturation or concentration of $\text{CO}_2$ in solution which would favor reaction 4 can be obtained either by 1) lowering the temperature and thereby increasing the solubility of $\text{CO}_2$, or 2) by encountering ground waters not themselves saturated in $\text{CO}_2$, in which the excess of $\text{CO}_2$ in the mineralizing solutions may be dissolved, or 3) by decreasing pressure, allowing for the escape of accumulated $\text{CO}_2$, or 4) by the formation of the bicarbonate ion.
Decreased temperature will also favor deposition of CaF$_2$ according to reaction 6 because its solubility decreases with lowered temperatures, whereas the solubility of calcium carbonate in carbonic acid solution increases with decreasing temperature, as indicated in reaction 5. Although lowered pressures will favor deposition of fluorite, according to reaction 4, deposition of calcite will also occur, due to the reversal of reaction 5.

It is assumed that the mineralizing solutions ascending along fractures were in a state of equilibrium because the limestone wall rock adjacent to the fractures, except at mineralized horizons, is not replaced by fluorite, nor has the limestone undergone solution. Upon reaching horizons at which the solutions were allowed or forced to migrate laterally, a temperature drop occurred favoring deposition of fluorite. This condition was present at the upper contact of the Fredonia, the Levias, and the Downey's Bluff or "Renault limestone". At the Fredonia and Downey's Bluff horizons, ground water present in the upper permeable horizons and in the overlying sandstones aided deposition of fluorite. The effect of two factors, 1) lowering temperature and therefore favoring fluorite deposition, and 2) encountering ground waters which would decrease the degree of saturation of CO$_2$ in the mineralizing solutions, help to account for the relative intensity of mineralization encountered in the Downey's Bluff and the Fredonia, as compared to the more weakly mineralized Levias.
CONCLUSIONS

The geology and mineralogy of the Minerva Mine No. 1 was the outgrowth of a study first undertaken to describe the nature and occurrence of witherite, identified by Dr. O. R. Graue in a specimen from this mine. Witherite had not been described previously from the Illinois-Kentucky fluor-spar area. Strontianite, which had not been described previously from this area was identified by the present writer. Both minerals were formed late in the mineralization process, and replaced barite, as well as being deposited from solution on other minerals. The paragenetic sequence of the non-sulphide minerals appears to be: fluorite, calcite, barite, strontianite, and witherite. Paragenetic relationships of the sulphide minerals were not definitely established. The sphalerite, chalcopyrite, and galena were formed after the first deposition of fluorite. The witherite was deposited after a period during which fluorite was dissolved in open channels and cavities. Minor deposition of fluorite and calcite occurred following the formation of the witherite. In the West Green Mine workings, which are nearer the surface than the Minerva Mine workings, the witherite exhibits the effect of late zonal solution by ground water.

The fluor spar deposits of the Minerva Mine No. 1 and other bedding replacement deposits in the Cave in Rook dis­trict are definitely related to the fracture system seen on the surface and in the mine workings. This fracture system
includes three sets of fractures, the most important of which strikes N. 50° E. to N. 55° E. The second set in importance strikes N. 55° W. to N. 60° W, and the third set strikes east-west. These fractures are steeply dipping or vertical and consist of minor normal faults and joints. Mineralizing solutions ascended along these fractures and spread laterally at favorable horizons to form the bedding replacement fluor spar deposits. The deposits are tabular, are elongated principally parallel to the N. 50° E. to N. 55° E. striking fractures, and are confined laterally within zones of closely spaced fractures. The fluor spar deposits therefore are closely related to the intersections of definite zones of fractures with definite stratigraphic horizons. At the Minerva Mine these horizons are the Fredonia limestone, the Levias limestone, and the Downey's Bluff or "Renault limestone".

It has been stated previously that the occurrence of an impervious cap rock was responsible for lateral migration of the mineralizing solutions beneath the cap rock. In the Minerva Mine, the Downey's Bluff, "Renault limestone", is most extensively and intensively mineralized. It is overlain by the Bethel sandstone, at the base of which occurs a 6 to 12 inch shale. The Levias limestone, which is most weakly and sporadically mineralized in the Minerva Mine, is overlain by the Shetlerville shale, which is an interbedded shale and limestone sequence. The thickest shale bed is
8 feet thick. The Fredonia limestone, which in the Cave in Rock district is the major mineralized horizon, is overlain by the Rosiclare sandstone, at the base of which a 6 to 12 inch shale occurs.

The stratigraphic distribution of the fluor spar deposits indicates that the permeability of the mineralized horizons was more important than the nature and thickness of the overlying cap rock. Original permeability was probably increased by subaerial weathering and by solution of the limestone by ground water obtained from the overlying sandstones. Therefore, the sandstones above the Downey's Bluff or "Renault limestone" and the Fredonia limestone are indirectly responsible for the lateral migration of mineralizing solutions and more important than the shales, which acted as cap rocks, in mineral localization.

Three types of ore textures occur in the bedding replacement deposits: banded or "coon-tail" ore, granular or massive ore, and disseminated ore. These types are related to the physical characteristics of the sediments in which they developed, and to the physical-chemical conditions prevailing at the time of mineral deposition. The development of the banded or "coon-tail" ore required volume replacement. Stoichiometric replacement of calcite by fluorite results in a 33 percent volume reduction. Openings so formed were immediately filled by deposition of fluorite from solution. The formation of the coarse granular, or massive
ore involved not only stoichiometric replacement of the limestone, but actual solution of the limestone. This was accompanied by the deposition of fluorite which did not keep pace with the rate at which openings were formed. Slump structures indicate the presence of large open cavities during the formation of the coarse granular or massive ore. The disseminated ore was developed by the incomplete and minor replacement of limestone by fluorite along bedding planes.

Mineral localization at favorable stratigraphic horizons was also controlled by physical-chemical conditions existing at these horizons. The limestone wall rock adjacent to the fractures along which the mineralizing solutions ascended are not replaced by fluorite or dissolved except at the mineralized horizons. Therefore, the ascending solutions were in equilibrium until they were forced or allowed to migrate laterally. Lowered temperatures at these horizons and the diffusion of $\text{CO}_2$ from the mineralizing solutions into ground waters at these horizons and in the overlying sandstones, upset the existing equilibrium and resulted in deposition of fluorite. The physical-chemical conditions prevailing in the Downey's Bluff, "Renault limestone" and in the Fredonia limestone were more favorable for the deposition of fluorspar than were the conditions which prevailed at the Levias limestone horizon.


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