UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL AND GEOPHYSICAL SURVEY OF FLUORSPAR AREAS IN HARDIN COUNTY ILLINOIS

Part 1. GEOLOGY OF THE CAVE IN ROCK DISTRICT
Part 2. AN EXPLORATORY STUDY OF FAULTS IN THE CAVE IN ROCK AND ROSICLARE DISTRICTS BY THE EARTH-RESISTIVITY METHOD

GEOLOGICAL SURVEY BULLETIN 942

UNITED STATES DEPARTMENT OF THE INTERIOR
Harold L. Ickes, Secretary
GEOLOGICAL SURVEY
W. E. Wrather, Director

Bulletin 942

GEOLOGICAL AND GEOPHYSICAL SURVEY OF FLUORSPAR AREAS IN HARDIN COUNTY ILLINOIS

PART 1. GEOLOGY OF THE CAVE IN ROCK DISTRICT

By L. W. CURRIER
WITH THE COLLABORATION OF O. E. WAGNER, JR.

PART 2. AN EXPLORATORY STUDY OF FAULTS IN THE CAVE IN ROCK AND ROSICLARE DISTRICTS BY THE EARTH-RESISTIVITY METHOD

By M. KING HUBBERT

Prepared in cooperation with the
STATE OF ILLINOIS
DEPARTMENT OF REGISTRATION AND EDUCATION
STATE GEOLOGICAL SURVEY DIVISION

UNITED STATES
GOVERNMENT PRINTING OFFICE
WASHINGTON : 1944

For sale by the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C.
Price $1.25

CONTENTS

ILLUSTRATIONS

FOREWORD

The manuscripts of parts 1 and 2 were transmitted to the Illinois Geological Survey in June 1937 and June 1938, respectively, for publication, according to a cooperative agreement between that bureau and the United States Department of the Interior, Geological Survey. Conditions since 1938 have interfered several times with plans made by the State bureau for publication of the report, so that the Federal Geological Survey offered to publish the report in order to avoid further delay. Accordingly, the manuscripts were returned to the Federal bureau in March, 1943.

Although the field work was done in 1934 and 1935 and the mine data and geologic data contained in the report are those that were obtained when the field work was done, it is believed that most of the information and discussions are as significant now as they were when the manuscripts were first prepared; the report is therefore published with little change, except for the revision of plate 19 to show production statistics up to 1940, the addition of data and references to the sections that deal with economic considerations and reserves, and an addendum in which significant mining and prospecting developments since 1937 are briefly reviewed. Publication of the report at the present time is particularly opportune in view of the current great need for additional supplies of fluorspar for purposes of national defense.

GEOLOGICAL AND GEOPHYSICAL SURVEY OF FLUORSPAR AREAS IN HARDIN COUNTY ILLINOIS

PART 1. GEOLOGY OF THE CAVE IN ROCK DISTRICT

By L. W. CURRIER

With the collaboration of O. E. Wagner, Jr.

ABSTRACT

The part of the Illinois fluorspar field known as the Cave in Rock district is characterized by horizontal deposits of fluorspar that have been formed by replacement of certain limestone beds in the Mississippian series of rocks. Unlike the vein deposits of the rest of the field, the Cave in Rock deposits occur at definite stratigraphic horizons. The principal ore horizon found so far is at the top of the Fredonia limestone member of the Ste. Genevieve limestone, just below the shaly base of the Rosiclare sandstone member. The Rosiclare sandstone is exposed along the east and south escarpments of Spar Mountain, a mesalike hill that rises about 200 feet above the adjacent lowland. Fluorspar deposits occur also at the same horizon at the top of Lead Hill, a small mesa near and southwest of Spar Mountain.

The present work seems to confirm the genetic theory previously published, namely that these deposits were formed by ascending solutions. These solutions probably followed minor fissures that connected below with larger fissures, which in turn probably connected with a major fault zone. It is believed that where such minor fissures extended upward only to the shale or other impervious cap rock, or were greatly reduced in size where they penetrated such beds, the solutions spread laterally along the contact and along the limestone beds beneath it and replaced the limestone. Differences in the texture and degree of purity of the limestone layers were among the factors that caused the layering of the ore. Stoichiometrical replacement (molecule for molecule) followed by further deposition is believed to have been the process that caused the crustification of the purer layers and the vug lines between them.

The bedding-replacement deposits of this district do not appear to be closely connected with major, regional faults, but rather with minor and local faults that are in turn probably related to the Peter's Creek major fault zone, that bounds the district on the northwest. The most favorable prospecting area, then, would be a belt generally parallel with the Peter's Creek fault but somewhat remote from it. Data obtained underground in all the accessible mines of the district seem to indicate that the fluorspar deposits are commonly localized on small local

folds as well as along minor fissures and that the long dimensions of the "ore" bodies are approximately parallel to the fold axes and the trends of the fissures; moreover, the structural axes and trends for the most part fall into two groups, one of which trends approximately N. 50° E.—generally parallel to the Peter's Creek major fault—and the other from N. 50° W. to N. 70° W., though a few structures fall outside these limits. The discovery of most of the minor structures, and particularly the folds, from surface geologic features alone would not be possible, however, because such features commonly do not extend far enough above the ore horizon to reach the surface, though several minor faults do appear at the surface.

Not only the northeast part of the mapped area, but also the unmapped area to the northeast of it should be considered favorable territory for prospecting. Particular attention should be given to evidences of minor structural deformation such as faults of even slight displacement, zones of closely spaced fissures, shattering and brecciation of formations, and reversed or unusually steep dips of the strata, in choosing sites for drilling. Such phenomena may lie along projections of the axes of similar phenomena known to exist in the mapped area and already developed mines, but, on the other hand, all zones of deformation will not necessarily be confined to such projected lines. Geophysical methods of exploration as described in part 2, by M. K. Hubbert, may aid materially in locating areas for drilling.

The Rosiclare sandstone horizon would be found at increasingly greater depths to the northeast, owing to the gentle but prevailing regional northeast dip of the formations.

It is reasonable to assume that bedding-replacement deposits of the Cave in Rock type probably occur in some other border areas of the Illinois-Kentucky field where lithologic sequences similiar to those of the Cave in Rock district occur and are somewhat remote from major faults. The presence of a shale or other compact and relatively impermeable bed overlying a thick limestone would be comparable to the lithologic sequences that appear to have influenced bedding replacement of limestone by fluorspar in the Cave in Rock district. The writer has found specimens of the banded type of fluorspar, such as characterize the Cave in Rock deposits, in dumps at the Hamp mines, on the north side of Hicks dome, and at the Renfro prospect, 4 miles east of Hicks. At both of these places the Rosiclare sandstone crops out. Charles Butts, of the Geological Survey, reported (unpublished manuscript) similiar specimens from the Rose prospect, near the center of Hicks dome, where the thick Chattanooga shale is exposed overlying Devonian limestone. Thus the lithologic sequences of beds and the geographic positions of these areas seem favorable for the existense of such deposits, but the structural details are not known.

LOCATION AND ACCESSIBILITY

The Cave in Rock district, as defined in this report, includes an area of approximately 3.3 square miles in the eastern part of Hardin County, Ill. It is about 4 miles northwest of Cave in Rock, a town on the Ohio River, which is the chief shipping point for fluorspar from this district. Cave in Rock is about 10 miles up the river from Rosiclare, a town which for many years has been the center of the fluorspar mining industry in Illinois, and which is the nearest railroad point to the Cave in Rock district. The district is reached by good highways from the north and west and a graded and graveled highway connects it with the town of Cave in Rock. There are no steep grades on the main roads between the producing area and the shipping points, Cave in Rock, Rosiclare, and Elizabethtown. The location of the district and its geographic relation to the rest of the Illinois-Kentucky field is shown on the key map, figure 1.

In 1935, two operators were conveying the milled fluorspar product by motor trucks to loading bins on the Ohio River at Cave in Rock; a third operator was trucking similar material to the railroad at Rosi-

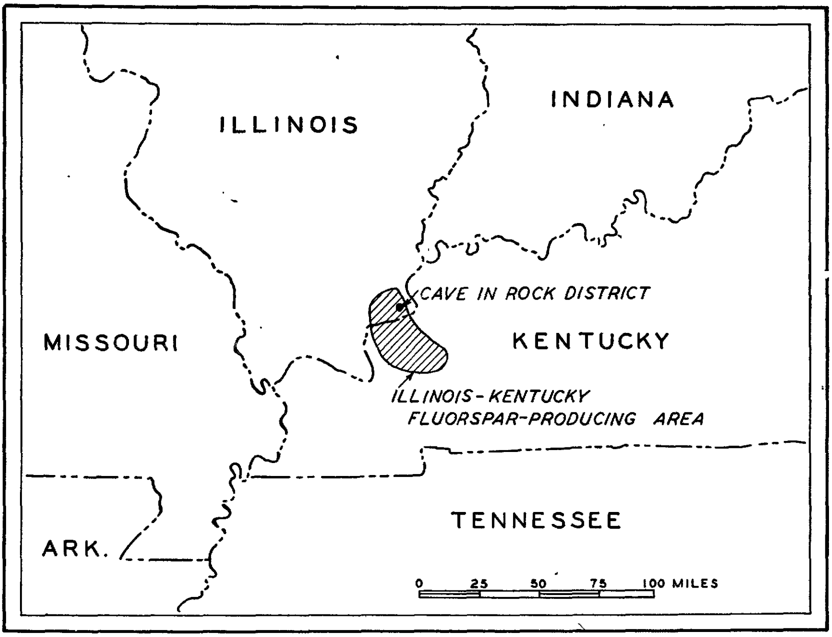


FIGURE 1.—Key map showing location of Cave in Rock district and its geographic relation to Illinois-Kentucky fluorspar field.

clare; and a fourth was trucking crude "ore" 13 miles to a mill reached by a railroad spur near Eichorn, about 5 miles northwest of Rosiclare.

FIELD WORK

In the summers of 1917 and 1919, the writer studied the fluorspar deposits of southern Illinois for the State Geological Survey, in connection with the geologic mapping of the area by Weller.[1] At that time the Cave in Rock district was but briefly examined, because only since then has it become an important producing area. In 1920 and 1921, the writer[2] studied the fluorspar deposits of the Kentucky part of the Illinois-Kentucky field.

[1] Weller, Stuart, and others, The geology of Hardin County, Ill.: Illinois Geol. Survey Bull. 41, 1920 (chapters on fluorspar deposits and on igneous rocks, by L. W. Currier).

[2] Currier, L. W., Fluorspar deposits of Kentucky: Kentucky Geol. Survey, ser. 6, vol. 13, 1923.

The field work upon which this report is based was done in July 1934 and July and August 1935. The first season's work was carried on by the Federal Geological Survey, under the auspices of the Public Works Administration, and in cooperation with the Illinois Geological Survey. The second season's work was done in continuation of the first season's work as a cooperative project between the Federal Geological Survey and the Illinois Geological Survey.

O. E. Wagner, Jr., mapped the formations of the district, and prepared the sections of the report that describe the details of stratigraphy and the individual faults. C. G. Dickinson served as instrument man of the party and prepared the topographic base map of the district and the maps showing contours of the Rosiclare sandstone.

While the surface mapping and mine studies were being carried on, M. King Hubbert made an earth-resistivity survey of the Cave in Rock and Rosiclare areas for the purpose of ascertaining how clearly and accurately hidden faults might be discovered by the resistivity method. The results of Mr. Hubbert's studies are given in part 2.

ACKNOWLEDGMENTS

The writer is greatly indebted to the several operators and mine managers in the district who readily gave free access to the mines, furnished mine maps and other important data, and facilitated the study in various other ways. Acknowledgment is also made of helpful discussions and advice on the part of E. F. Burchard and other colleagues in the Federal Geological Survey.

IMPORTANCE OF CAVE IN ROCK DISTRICT

This special study of the Cave in Rock district was occasioned by the rapid rise in industrial importance of the district since 1919, and by significant geologic features uncovered by mining developments, mostly since 1926. The rapidly growing importance of the district is indicated by the statistics of production, which show an increase in the output of crude ore[3] from 9,930 short tons in 1919 to 32,295 short tons in 1930. Since 1930 the production has fluctuated greatly. Of fluorspar shipped from the Illinois-Kentucky field in 1919, 1929 (peak year), and 1934 (last year for which statistics were available), the Cave in Rock district furnished 5.5 percent, 11.7 percent, and 16.7 percent, respectively.[4] Economic features are discussed further on subsequent pages.

---

[3] Technically, the term "ore" is used only to denote a mine product from which a metal is obtained, but in this district the operators apply it to fluorspar bodies of commercial importance, and it is therefore used in this sense throughout this report.

[4] Statistics furnished by H. W. Davis, Div. Mineral Statistics, U. S. Bur. Mines. For total production since this report was prepared see page 71; in 1940 the Cave in Rock district produced 24.0 percent of the Illinois-Kentucky production.

The high quality of the Cave in Rock ores and the relatively low mining and milling costs give the district a distinct advantage over much of the field.

The Cave in Rock district is on the margin of the extensive Illinois-Kentucky fluorspar field, which is probably the largest and most productive area in the world for this mineral. As regards the major features relating to the geology and origin of its deposits, the Cave in Rock district is not materially different from the rest of the field; as regards details, however, not only of structure and origin, but also of economic development, the district has so many distinctive features that affect methods of prospecting and development as to deserve separate description.

GEOLOGIC FEATURES OF THE ILLINOIS-KENTUCKY FIELD

A brief description of the principal geologic features of the entire Illinois-Kentucky field is presented at this point in order to make clear the genetic relationship between the bedding-replacement deposits of the Cave in Rock district and the vein deposits which characterize the rest of the field. Detailed descriptions of the geology of the field and discussions of the fluorspar deposits have appeared in earlier publications.[5]

STRATIGRAPHY AND STRUCTURE

SEDIMENTARY FORMATIONS

The formations exposed in the area comprise sedimentary rocks of Devonian and Carboniferous (chiefly Mississippian) age, and several small igneous bodies whose age is post-Carboniferous—possibly late Cretaceous or early Tertiary. The rocks are cut by a great number of normal faults, giving marked distinction to this part of the Mississippi Valley province. The structural picture displayed by the map (fig. 2) is that of a broadly domed area that has collapsed into a mosaic of fault blocks and wedges. The longer diameter of the dome trends northwestward and its length was originally more than 30 miles. In the northwest portion of the field there is a subordinate structure known as Hicks dome, at the center of which are exposed a middle Devonian limestone and the Chattanooga shale, which is of upper Devonian (and lower Mississippian?) age. The limestone is the oldest rock exposed in the field.

[5] Weller, Stuart, and others; The geology of Hardin County, Ill.: Ill. Geol. Survey Bull. 41, 1920. Weller, Stuart, Geology of the Golconda quadrangle: Kentucky Geol. Survey, ser. 6, vol. 4, 1921; Geology of the Princeton quadrangle: Kentucky Geol. Survey, ser. 6, vol. 10, 1923; Geology of the Cave in Rock quadrangle: Kentucky Geol. Survey, ser. 6, vol. 26, 1927. Currier, L. W., Fluorspar deposits of Kentucky: Kentucky Geol. Survey, ser. 6, vol. 13, 1923. Bastin, E. S., The fluorspar deposits of Hardin and Pope Counties, Ill.: Illinois Geol. Survey Bull. 58, 1931.

The stratigraphic sequence is shown in figure 3. Its most important features so far as the fluorspar deposits are concerned are (1) the great thickness (about 1,400 feet) of limestone beds between the Bethel sandstone and the Chattanooga shale; (2) the presence of a thin sandstone member (the Rosiclare sandstone) near the top of this limestone sequence; and (3) the numerous relatively thin beds of

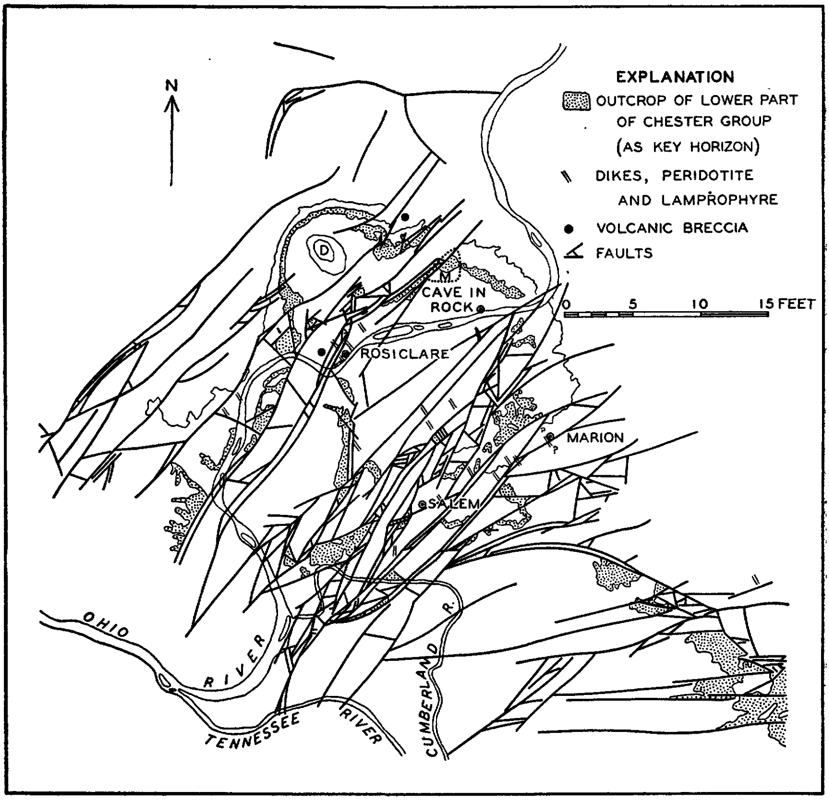


FIGURE 2.—Condensed geologic map of Illinois-Kentucky field. Area within dotted line and marked M is that covered by geologic map (pl. 3). D represents outcrop of Devonian strata. Compiled from maps by Stuart Weller, Charles Butts, and A. H. Sutton. Courtesy of J. M. Weller.

alternating sandstones, limestones, and shales of the Chester group, in which siliceous beds are dominant.

IGNEOUS ROCKS

Dikes and sills of mica peridotite and lamprophyre cut the sedimentary rocks. The many known occurrences are broadly distributed through the field but are mostly well within the domed area. All the known dikes trend northwestward parallel to the major axis of the dome, and, as they do not occupy fault fissures and some are cut by fluorspar veins, it is believed that they were intruded before the period of general faulting.

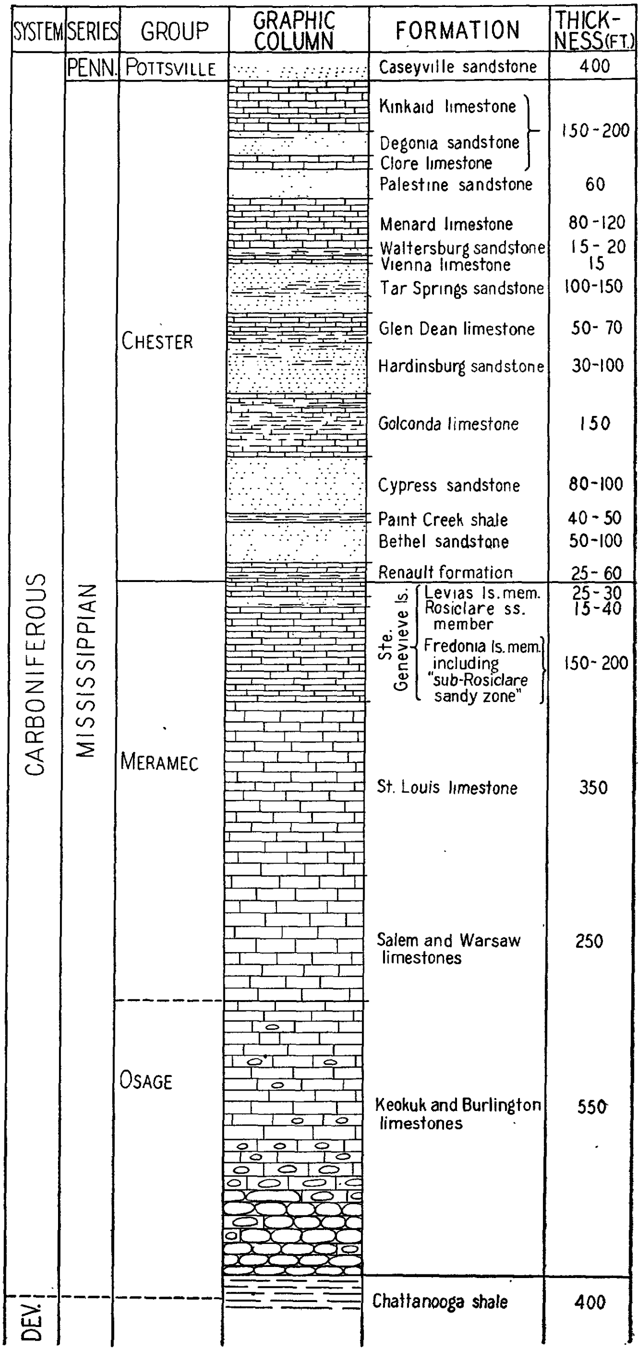


FIGURE 3.—Generalized columnar section of formations exposed in the Cave in Rock district.

At two places, siliceous clastic material, which from its apparent mode of occurrence and composition may be of volcanic origin, occurs in the Illinois part of the field.

A few veins of fluorspar border and cross dikes, but in general there is no common coincidence in occurrence of veins and igneous rocks.

FAULTS

The formations of the Illinois-Kentucky field are cut by a great number of normal faults, which range in displacement up to 1,500 feet. The major faults and many of the minor faults have northeast-southwest trends, approximately at right angles to the longer axis of the dome, and some of these extend far into the border areas of the dome. To the southeast the major fault zones become progressively more easterly in trend and merge into a narrow belt of east-west faults that extends into central Kentucky. On the west, another belt of fractures extends almost continuously into the highly faulted area of Ste. Genevieve County, Mo.

FLUORSPAR DEPOSITS

The fluorspar deposits of the Illinois-Kentucky field have been classified as (1) vein deposits, (2) "blanket," "bedding," or "bedding-replacement" deposits, and (3) superficial deposits. The vein deposits have been described in several previous reports, but their main features will be summarized briefly here, in order to show their genetic relation to the bedding-replacement deposits that characterize the Cave in Rock district. The terms "superficial deposits" and "gravel deposits," applied to local concentrations in the clay mantle at the apices of veins, are of economic rather than geologic significance. The "bedding" or "bedding-replacement" deposits, which are mined only in the Cave in Rock district, were formed by replacement of limestone strata beneath denser cap rocks; they have been called "blanket deposits" by some geologists. The term "blanket deposit" has also been applied by some to the superficial deposits of this area, but although it is a broad term as applied to ore deposits its generally accepted significance is distinctly different from the term as applied to either the "bedding-replacement" or "gravel" deposits of this field,[6] and the terms "bedding" and "bedding-replacement" deposit seem far more satisfactory for use in the Cave in Rock district. The term "blanket" is particularly confusable with the use as applied to deposits of the Joplin district, and "chalcocite blankets" as used by Lindgren.[7] The term "bedded deposit" has been rejected because it suggests that the deposits were laid down by sedimentary processes.

---

[6] Fay, A. H., Glossary of mining terms: U. S. Bur. Mines Bull. 95, 1920.

[7] Lindgren, Waldemar, Mineral deposits, 3d ed., pp. 712 et seq., New York, McGraw-Hill Book Co., 1928.

The fluorspar veins were deposited in fault fissures, partly by direct precipitation of the fluorspar and partly by replacement of limestone wall rock and an earlier vein filling of calcite. The coarse vein calcite was derived probably in part from brecciated limestone wall rocks by recrystallization through the agency of ascending thermal waters, and in part by transportation from beds at lower horizons. In general, developments show that the larger fluorspar bodies are found where at least one wall is within the thick limestone formations below the Bethel sandstone. The thinner beds of limestone alternating with noncalcareous formations in the Chester group, above the Ste. Genevieve limestone, were apparently much less favorable sites of deposition for large or continuous ore bodies.

The veins commonly pinch or disappear between walls of shale, or shale and sandstone. This lithologic selectivity, together with the marked degree to which calcite is replaced by fluorspar, bespeaks the strong influence of calcareous material in the veins and wall rocks on the fixation of fluorine from the original solutions.

Sulfides, chiefly galena and sphalerite, are prominent in some veins and absent from others, and were deposited later than most of the fluorspar, after a period of fracturing that reopened old fissures or developed new minor fissures within the fluorspar bodies or even entirely new fissures not related to earlier faults. The sulfides partly replaced the calcite and fluorspar of earlier deposition although they were doubtless derived from the same ultimate source as the fluorspar. As the sulfides most commonly were deposited in fractures in the fluorspar and calcite veins, sulfide deposits not associated with fluorspar are comparatively uncommon, though there are many fluorspar veins devoid of sulfides.

Quartz was deposited in some veins, particularly along secondary fissures, so that some of the fluorspar bodies are siliceous. Some recrystallization of sandstone wall rocks took place to form quartzite, that by virtue of superior hardness and resistance to erosion forms quartzite "reefs," some of which mark the courses of fault zones.

At the Daisy mine of the Rosiclare Lead and Fluorspar Co., vein material has been followed to a depth of 800 feet, the greatest depth yet reached in the Illinois-Kentucky field. How much deeper the vein continues is not known, nor are there sufficient data to indicate an average or consistent rate of decrease in fluorspar content. Also there is no apparent stratigraphic limitation of the veins. At a depth of about 400 feet one shaft in Kentucky penetrates the Warsaw limestone; the same formation is reached in one wall of the Rosiclare vein at 500 to 600 feet. It is probable that the thermal gradient as well as the character of wall rocks determined the depth of the zone in which fluorspar was precipitated. The thermal gradient was doubtless relatively low, a condition that would be favorable for the formation of fluorspar bodies through a thicker zone, than in cases where the gradient was relatively high, as in many of the western ore deposits. The calcareous nature of the wall rocks apparently was a very influential factor, providing the most favorable chemical environment for the fixation of fluorine as fluorspar. As there is known to be a total thickness of about 1,200 feet of limestone below the Ste. Genevieve formation in the fluorspar field, it seems reasonable to assume that fluorspar bodies may exist at much greater depths than has been demonstrated so far, and that in some places, they may extend well into or even through the Osage group.

This view may not seem to be supported by the apparently restricted stratigraphic range of the Cave in Rock bedding-replacement deposits, although their fluorine is believed to have had the same source as that in the veins. For reasons discussed more fully below, the localization of the Cave in Rock deposits is believed to have been dependent upon the presence of dense strata within beds of permeable strata, and minor fracturing. Extensive deposits of this type at greater depths than those at which such deposits have been found in the Cave in Rock district are not indicated by any available data, though such deposits might conceivably be found at any stratigraphic horizon within the temperature range of fluorspar deposition where structural and lithologic conditions were favorable. Fluorspar has been found in the St. Louis limestone, which underlies the Ste. Genevieve, about a quarter of a mile northeast of Tower Rock school, where it appears to occur along the bedding of the rock, but the exposures at this place were not sufficient to determine whether or not this fluorspar represents a bedding-replacement deposit of the type that characterizes the Cave in Rock district.

GEOLOGIC FEATURES OF THE CAVE IN ROCK DISTRICT

TOPOGRAPHY

The Illinois portion of the fluorspar field lies in an area of maturely dissected plateau land, that some geologists regard as a spur of the Ozark plateau.[8] Many of the divides are narrow, nearly flat-topped ridges and the intervening valleys are likewise narrow and V-shaped. (See pl. 1.) The summits of the divides for the most part reach a general altitude that, according to Salisbury,[9] marks an imperfect peneplain developed by early erosion of the uplifted Ozark Plateau. Most of the present ridge tops and mesalike areas are remnants of this plain, the uplift of which quickened the streams and caused a deepening of the valleys, with a consequent development of blufflike valley walls in places where the bedrock formations were most resistant. Some of the exceptionally straight and persistent valleys, bluffs, and ridges

[8] Weller, Stuart, and others, The geology of Hardin County, Ill.: Illinois Geol. Survey Bull. 41, 1920, p. 19.
[9] Idem, p. 47.

mark the positions of faults, whereby bedrock formations of different degrees of resistance were brought into juxtaposition previous to the uplift and dissection of the peneplain. Subsequent erosion caused the more resistant beds in one wall of each of the faults to form the present bluffs and ridges.

Several areas bordering the Ohio River, on the other hand, are either flood plains of this stream or areas underlain by thick and soluble limestone formations. The northern and eastern parts of Cave in Rock township in particular comprise a broad limestone area whose altitude (about 400 to 460 feet above sea level) is roughly 150 to 200 feet lower than the summits of the adjacent area. In this lowland, underlain by the St. Louis and Fredonia limestones, much solution of the limestones by underground waters has taken place, so that many sinkholes have been developed, and a thick mantle of insoluble residual clay soil has accumulated. Such an area is particularly difficult ground for prospecting, even though the lithology and structure of the rocks may be favorable, for the ordinary indications of faults and veins or other mineral bodies are generally completely obscured.

On approaching Cave in Rock district from the south, one is faced by a steep bluff that rises about 200 feet above the general level of a lowland in which there are numerous sinkholes. The escarpment continues northwestward for a mile without being interrupted by prominent valleys. Midway in this stretch there is a broad indentation as if a block were offset by cross faulting; there is no certain evidence of a fault here, however. At the northeast end of this mile a pronounced steep-walled valley having a N. 40° W. trend cuts through the escarpment. The regularity of the drainage pattern of this valley and its tributaries suggests adjustment to geologic structures, particularly faults, and surface geologic evidence together with geophysical data indicate that some minor faults are present. Plate 2 displays the drainage pattern of the district, and the geologic map (pl. 3) shows where available data suggest the presence of faults.

West of the plant of the Benzon Fluorspar Co. (see pl. 1), the escarpment broadens, and from a point about a quarter of a mile west of the plant it trends approximately N. 40° W. for a distance of three-fourths of a mile to Peters Creek. There may be some structural significance in the fact that this direction of trend is practically parallel to a minor fault a quarter of a mile west of the Benzon plant, and is also parallel to the previously mentioned valley at the northeast end of the mapped area.

Near the middle of the northwestward-trending escarpment a broad low saddle separates the escarpment from a hill to the southwest. This saddle is nearly bisected by two very minor creek valleys in alinement, heading toward each other, and draining to the northwest and southeast, respectively. The axes of these valleys trend about N. 30° W., approximately parallel to the trends previously mentioned. Some prospect holes on the saddle, between the valleys, have shown fluorspar, but there are no rock exposures, so that the existence of a fault trace along these valleys could not be proved.

An eighth of a mile southwest, the broad low saddle connects with the north end of Lead Hill, a short, narrow, flat-topped, north-south ridge about half a mile in length. Lead Hill is a buttelike feature in which the underlying strata are nearly horizontal, and which has been isolated from Spar Mountain by erosion. The crest of Lead Hill is at an altitude of 660 feet above sea level, or 160 to 170 feet above the level of the surrounding plain. Several fluorspar prospects and small mines are situated around the south end and along the east side of the ridge.

The top of the Spar Mountain mesa is at an altitude of slightly more than 670 feet above sea level at a point on the edge of the escarpment a few hundred feet west of No. 2 shaft of Victory Fluorspar Co. (see map, pl. 1). The general altitude of the top of the escarpment along the south side of Spar Mountain is about 640 to 650 feet. The top surface of the mesa slopes gently northward from this locality nearly to the northwest limit of the mapped area where the general altitude is 550 feet along a narrow northwestward-trending belt. On the northwest side of this relatively low belt, the surface rises comparatively steeply to an altitude of slightly more than 700 feet, forming another escarpmentlike feature trending approximately N. 50 E. to the limits of the mapped area. This escarpment continues the line of Peters Creek, north of Lead Hill, and marks the zone of faulting known as the Peters Creek fault zone, the only major fault zone known to exist in the district. The similarity in trend of this escarpment to the trends of several minor valleys on Spar Mountain (pl. 2) and to the general trend of the escarpment that forms the southeast side of the mesa suggests that the positions of these valleys may have been controlled by faults, but this interpretation is not supported by any available stratigraphic evidence.

To the northwest of Peters Creek fault escarpment the general surface merges into the characteristic mature topography of Hardin County.

The lowland comprising the southern and eastern parts of the mapped area is part of the large area of sinkholes that, as already mentioned, covers a large proportion of Cave in Rock township. In the mapped area, this lowland is directly underlain by the Fredonia limestone, the top of which is the chief horizon for fluorspar deposits. This horizon is exposed close to the top of Lead Hill at its south end and midway up the Spar Mountain escarpment, but as fluorspar has also been prospected at a lower stratigraphic horizon, on a knoll in the flats east of the escarpment, a part of the lowland has been included in the map of the district.

The lowland has a gently rolling surface and contains several broad, shallow depressions, or sinkholes, which are drained through underground channels. The largest sinkhole is in the southeastern part of the mapped area and covers nearly half a square mile of this area besides nearly a square mile of adjacent territory to the east and south. The rim of this sink is approximately at an altitude of 420 feet. In times of continued and heavy rains the sink has filled with water nearly to the 400-foot level, forming a broad shallow lake almost a mile across; generally, however, the submerged area is much less. Drainage of this sink is very slow at times and a considerable body of water may stand in it for several months. Many small sinks are scattered over the rest of the mapped lowland, and at times contain ponds that are drained very slowly. At times the sinkhole ponds extend over the roads leading from the main highway to the mines so that, in order to maintain access, it is necessary to elevate sections of the roads by filling.

There are no physiographic features in the lowland area that suggest influence of geologic structures upon the topography.

STRATIGRAPHY

GENERAL STATEMENT

All bedrock formations exposed in the Cave in Rock district are of sedimentary origin; they consist of limestones, sandstones, and shales belonging to the Mississippian and Pennsylvanian series of the Carboniferous system. Igneous rocks, though known to be present in other parts of Hardin County, have not yet been discovered in this district.

The formations are nearly horizontal, with a slight general regional dip to the north and northeast, except where they have been disturbed by local faulting that has produced slight to moderate dips in other directions.

The lowest unit exposed in the area is the Fredonia limestone member of the Ste. Genevieve limestone, which constitutes the bedrock of the lowlands and the lower parts of the slopes in the southwestern and southern parts of the area. Successively higher formations of the entire Chester group are exposed toward the north, the sequence being broken in places by faults. One formation, the Palestine sandstone, is not exposed, because of faulting, but all other formations of the Chester group are exposed at one or more places in the district. The highest formation exposed is the Caseyville sandstone, of lower Pennsylvania age, which caps the escarpment of a down-faulted block of the Peters Creek fault zone in the northwest part of the district. The distribution of outcrop areas of the numerous formations is shown by the geologic map, plate 3, and a generalized columnar section of the formations is shown in figure 3.

DESCRIPTIONS OF FORMATIONS

By O. E. Wagner, Jr.

MISSISSIPPIAN SERIES

ST. LOUIS LIMESTONE

Although it is not exposed within the limits of the mapped area, the St. Louis limestone crops out not far to the south, along the Ohio River, extending continuously from Hosick Creek, about 2 miles east of Elizabethtown, to a point about half a mile east of Cave in Rock. The belt of outcrop is about 2 miles wide at its widest point. From this belt the formation dips northward under younger rocks of Mississippian age, and in the Cave in Rock mining district it lies beneath the surface, being probably about 100 to 125 feet below the base of the escarpment at the Benson Fluorspar Co. mill.

The St. Louis limestone is commonly a hard, dense rock, mostly dark blue or almost black in color on fresh surfaces and light bluish-gray and smooth when exposed to weathering. Some beds of crystalline limestone occur in the formation; oolitic beds are almost entirely absent. Chert is quite common and is usually dark colored where fresh and lighter where exposed to weathering; it occurs as lenticular and irregular masses in planes parallel to the bedding of the limestone. The thickness of the St. Louis limestone in Hardin County, Ill., is estimated by Weller to be about 350 feet. The exact position of its contact with the overlying Fredonia limestone is very difficult to determine but it is usually placed below the lowest oolitic beds in the section.

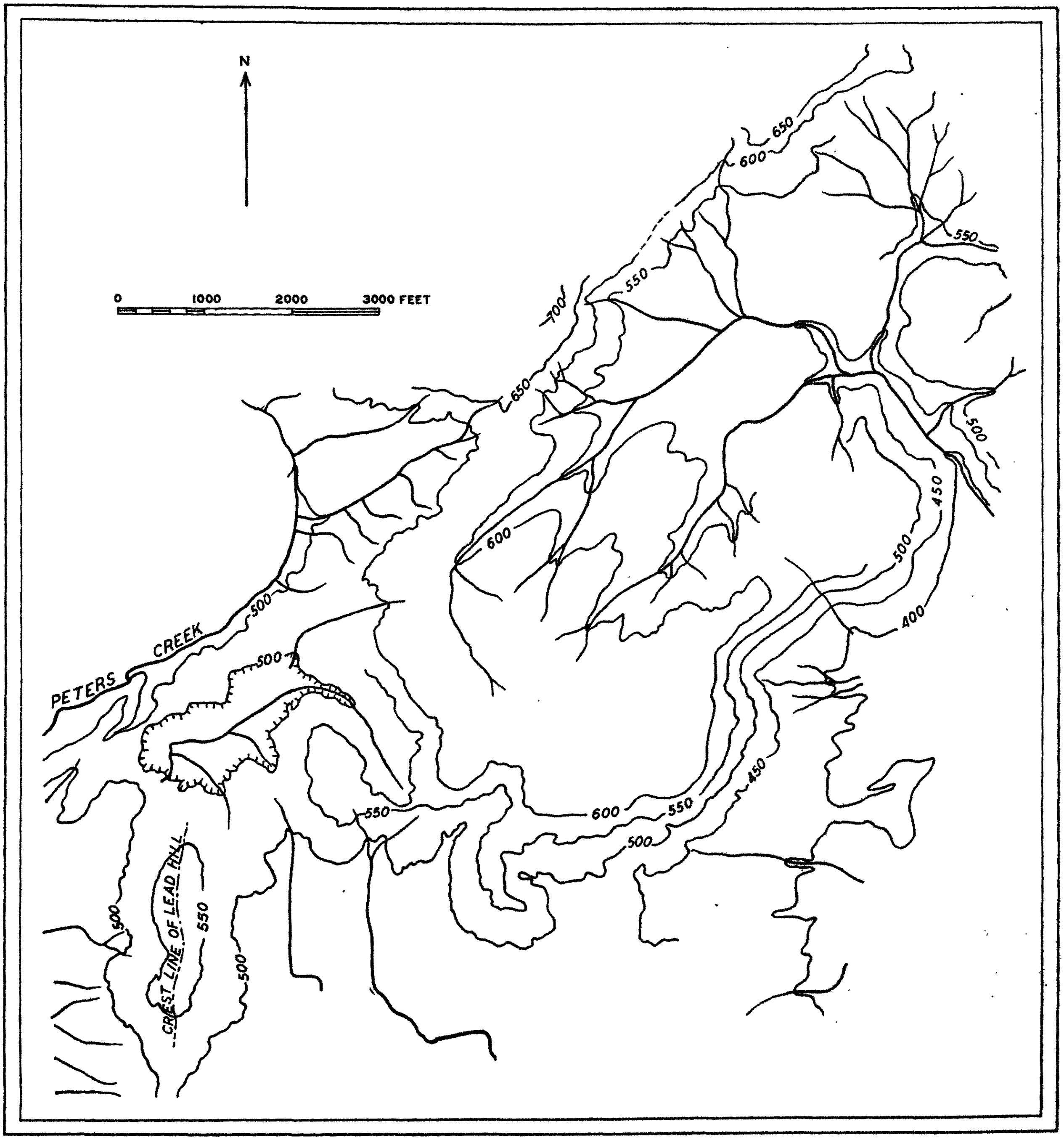
Fluorspar has been found in the St. Louis limestone at several small prospect pits located in the SW¼SE¼ sec. 17, T. 12 S., R. 9 E., about a quarter of a mile northeast of Tower Rock school. It appears to occur as deposits along the bedding of the rock.

A little mining, chiefly of lead carbonate (cerussite) has been done also in the SW¼NW¼ sec. 16, T. 12 S., R. 9 E., in what appears, from the chert on the mine dumps., to be St. Louis limestone. Slickensided rock on the mine dumps indicates a fault, but no exposure of the fault was seen.

STE. GENEVIEVE LIMESTONE

The Ste. Genevieve limestone formation consists of three members, the Fredonia limestone (oldest), the Rosiclare sandstone, and the Levias limestone (youngest).

Fredonia limestone member.—The Fredonia limestone is the lowermost and thickest member of the Ste. Genevieve limestone. It con-



MAP SHOWING DRAINAGE PATTERN OF CAVE IN ROCK DISTRICT.

sists essentially of even-bedded limestone which is variable in lithologic character, but which, especially in the upper 75 feet, is markedly oolitic. The oolitic beds are white on weathered surfaces and in places show cross bedding, especially at and near the top of the member. Interbedded with the oolitic beds are beds of gray limestone, of which some are crystalline and fossiliferous and some are dense and almost as fine-grained as lithographic limestone, breaking with a conchoidal fracture. The crystalline beds weather light gray, either with smooth surfaces or with surfaces that are studded with fossils, prominent among which are the elliptical stem plates of the crinoid *Platycrinus penicillus*. Some of the dense beds weather with smooth buff-colored surfaces.

The Fredonia limestone underlies the extensive sinkhole plain in the southern part of the district, but outcrops are scarce there and are usually found only in some of the gullies and in the deeper sinks. This limestone is well exposed around the base of Lead Hill and along the Spar Mountain escarpment from the Crystal mine southwestward and westward to the easternmost branch of the Peters Creek fault zone; outcrops are generally quite good in these areas.

From 50 to 65 feet below the top of the Fredonia limestone member there is a markedly cross-bedded, sandy limestone, which is known locally as the "sub-Rosiclare sandstone" and which ranges from a few inches up to 11 feet in thickness. It can be traced around the foot of the Spar Mountain escarpment from the old lower workings of the Cave in Rock mine eastward and northeastward to the low hill south of the Crystal mine. To the west, on Lead Hill, it appears to have thinned out or is not of mappable thickness. In outcrop this rock is extremely porous because of the leaching of the calcareous material by weathering processes.

The full thickness of the Fredonia limestone is not revealed in the district and the base has not been reached by either shafts or drill holes. Its total thickness in Hardin County, Ill., is about 180 to 200 feet[10].

Rosiclare sandstone member.—The Rosiclare sandstone member of the Ste. Genevieve limestone overlies the Fredonia limestone member, with which it appears to be conformable. It is fine grained, and porous and yellowish brown where weathered; its beds are usually thin, averaging about 2 inches in thickness, but in places, as on the north end of Lead Hill, they are thicker and resemble sandstone beds of higher formations; generally, however, the Rosiclare sandstone can readily be distinguished from sandstone of the Chester group. The unweathered Rosiclare sandstone is a very sandy limestone or calcareous sandstone which is gray in color and quite compact. The

10. Weller, Stuart, and others, The geology of Hardin County, Ill.: Illinois Geol. Survey Bull. 41, pp. 113-114, 1920.

leaching out of the lime by weathering produces the sandstone of porous texture. In thickness the Rosiclare sandstone member varies from 15 to 40 feet, but the average thickness is about 25 feet.

At the base of the Rosiclare sandstone, and resting upon the Fredonia limestone, is a green sandy shale which varies considerably in thickness within short distances. On the north end of Lead Hill this shale is apparently absent, but an eighth of a mile northeast, in an old shaft on the Martin property, 8 feet of the shale was penetrated. Ordinarily its thickness ranges from 6 inches to a foot or slightly more.

The Rosiclare sandstone is exposed around Lead Hill and along Spar Mountain escarpment from the east branch of the Peters Creek fault zone (fault No. 3, pl. 3) eastward to the edge of the district. It is exposed at the top of the south end of Lead Hill, but because of its gentle northerly dip its outcrops are 70 to 80 feet lower at the north end of the hill. From the escarpment of Spar Mountain it dips northward and underlies younger formations. Its contacts, both with the underlying Fredonia limestone and with the overlying Levias limestone, can readily be traced. Its outcrop declines gradually northeastward along the escarpment so that in the eastern part of the mapped area, in the latitude of the Crystal mine, it passes below the surface. Northwestward along the southwest side of Spar Mountain it gradually leaves the escarpment and passes into a sinkhole area, where it is abruptly terminated by the Peters Creek fault. In the area between Lead Hill and Spar Mountain it appears at the top of the westernmost of two low knolls and around the sides of the easternmost. A large number of contacts with the Fredonia limestone can be seen in the many mine adits, open pits, and cuts in the district.

Levias limestone member.—Overlying the Rosiclare sandstone member is the Levias limestone member of the Ste. Genevieve limestone. This limestone is almost indistinguishable, except for its stratigraphic position, from the Fredonia limestone. It consists of interbedded oolitic limestone and gray, crystalline to lithographic limestone, with thin partings of shale. It is thin-bedded at the base, and thicker-bedded toward the top. The oolitic beds are not as white in this area as the oolitic beds of the Fredonia limestone.

Good exposures of the Levias limestone member can be seen on the escarpment in the vicinity of the old Cleveland mine, in a gully north of the logwasher on the Martin property, and on Lead Hill. In these places the Levias limestone member consists of fairly thick beds of limestone with a total thickness of 25 to 30 feet. Elsewhere the outcrops are partly covered, so that the contacts can be judged only from the topography, but nearly everywhere it is better exposed than limestone and shale beds of the overlying Renault formation.

The name "Levias limestone" was proposed in 1932 by J. M. Weller and A. H. Sutton, to supplant the term "Lower Ohara," the term that appears in earlier reports on the Illinois-Kentucky field.

CHESTER GROUP

Renault formation.—The Renault formation consists of interbedded light gray to bluish-gray and brown limestone and gray, green, and red shale. The limestone beds are more or less oolitic, fossiliferous and argillaceous, and range in texture from very fine to coarse. They weather with smooth surfaces, which may be gray, but lighter than the fresh rock, or yellow to light brown. Ordinarily the Renault formation is covered with talus derived from the overlying Bethel sandstone, and in most of its outcrops only the limestone is exposed; fragments of a gray calcareous shale may be seen, however, on the dumps of several prospect pits. Nowhere was an exposure found in which a section of an appreciable thickness could be measured.

The Renault formation extends along the Spar Mountain escarpment, where its distribution is generally similar to that of the Levias limestone member. It also occurs on the top of Lead Hill and on the higher of the two knolls between Lead Hill and Spar Mountain. It is exposed in the bottom of a large sinkhole just north of the mill ponds of the Victory Fluorspar Co., on the sloping top of Spar Mountain.

As shown by records of diamond-drill borings, the interval between the Bethel sandstone and the Rosiclare sandstone ranges from 55 to 80 feet. As this interval is occupied by the Levias member and the Renault formation, the latter probably ranges from 25 to 60 feet in thickness.

Bethel sandstone.—A large part of the Cave in Rock district is directly underlain by the Bethel sandstone. This resistant formation constitutes the upper part of the Spar Mountain escarpment, and much of the sloping upland plain north of the escarpment consists of dip slopes of the sandstone.

Wherever seen along the top of the escarpment the Bethel sandstone is a massive irregularly cross-bedded sandstone that forms a steep bluff, skirted with talus which obscures the contact of the sandstone with the underlying Renault formation. The sandstone is fine-grained, compact, and yellowish-brown. Freshly broken pieces show characteristic large, uniformly distributed brown spots. Where the sandstone is exposed in the gullies and valleys along the dip slopes its massive character is not evident. The upper beds of the Bethel sandstone, near its contact with the Paint Creek formation, are thin, somewhat shaly, and lighter in color than the lower beds.

Paint Creek shale.—The Paint Creek shale is exposed at only a few places in the district and the mapping of this formation was done mainly on the basis of topographic expression. The best exposures are in the northeastern part of the district, along the northward-flowing creek about a quarter of a mile north of the Crystal mine, and in the creek valley an eighth of a mile farther northeast. A shale which is believed to be the Paint Creek shale is also revealed in an old shale on the middle fault of the Peters Creek fault zone.

The best measure of the thickness of the shale was obtained in the exposure north-northeast of the Crystal mine where the full thickness is 12 feet; in places, however, the shale may be as much as 20 feet thick. Wherever seen it is dark gray and thinly laminated, and contains interbedded thin layers of sandstone.

Cypress sandstone.—The Cypress sandstone, like the Bethel sandstone, is for the most part massive, irregularly cross-bedded, yellowish-brown to white, fine-grained, and compact. The upper part is thin-bedded and contains at least one conspicuous bed of light gray shale.

This sandstone forms the capping of the Spar Mountain mesa an eighth of a mile north of the Crystal mine, and also occurs in a strip that crosses the northern part of the area. This strip is narrow near the Peters Creek fault zone, where the dip is relatively steep, and broadens out eastward where the dips are not so steep. Two of the blocks of the faulted zone on the west side of the district, have been mapped as Cypress sandstone, but the identification is not made with absolute certainty.

No complete section of the Cypress sandstone is exposed in the area, but from data obtained in adjoining areas it is estimated to be 100 to 125 feet. There is a marked unconformity at its base.

Golconda limestone.—The Golconda limestone is made up of three intergrading parts, the upper part consisting of coarse-grained, oolitic limestone, the middle part of shale, and the lower part of argillaceous limestone and shale. It is the most poorly exposed formation in the district. It has been mapped partly from scattered exposures in the gullies along the base of the Peters Creek fault escarpment in the northern part of the district, but its distribution has to some extent been inferred from the topography. The scattered exposures in the Cave in Rock district are mostly of dark gray coarsely crystalline limestone, and do not reveal the shale which, to judge from better exposures in other parts of Hardin County, probably makes up the greater part of the formation.

The thickness of the formation in the district could not be determined, but in other places where it is better exposed the formation is from 100 to 150 feet thick.

Hardinsburg sandstone.—The Hardinsburg sandstone is moderately fine-grained, compact, and white to gray where it is not weathered; weathered surfaces are darker, commonly dark brown. It contains some beds of sandy shale, especially near the base, which grade into massive beds of sandstone resembling those of the Cypress and Bethel sandstones.

Exposures of the Hardinsburg sandstone are meager, and in no place can a complete section of it be seen. It is exposed in short, narrow bands at several places along the Peters Creek fault zone. In the extreme northern part of the district, a band of this sandstone diverges from the fault zone and extends eastward, through a broader area of outcrops, beyond the mapped area. Along the Peters Creek fault escarpment the talus from the Caseyville sandstone covers most of the Hardinsburg sandstone. A good exposure, showing regular beds of white to gray sandstone, occurs at the northern end of the mapped area, along an old road west of the present Forest Service road.

No exact determination of its thickness was possible, but the formation is probably about 100 feet thick.

Glen Dean limestone.—Like the Golconda, the Glen Dean limestone is made up of both shale and limestone beds, but limestone predominates. Its only exposures in the mapped area are in the small block northwest of the Peters Creek fault zone, along the valley of Peters Creek. Outcrops of the gray, crystalline limestones just below the contact with the overlying Tar Springs sandstone, can be seen along the wagon road on the west side of this block. On the tributary to Peters Creek just east of the house in the southwest corner of the block there is an outcrop of crystalline, gray, fossiliferous limestone; the fossils include the bryozoan *Prismopora serrulata*, which is characteristic of the Glen Dean limestone. Blocks of a brecciated, dark-gray, crystalline limestone, with calcite veins, that is believed to be the Glen Dean were seen on the dump of an old prospect shaft near the north end of the middle fault of the Peters Creek fault zone.

At no place in the district is the full thickness of the Glen Dean limestone exposed. In other parts of Hardin County it attains a thickness of from 50 to 70 feet, according to Weller.[11]

Tar Springs sandstone.—The Tar Springs sandstone, like the Glen Dean limestone, is well exposed northwest of the Peters Creek fault zone. It is at the surface in a large part of this block, and is probably present also in the block bounded by faults 1, 2, and 6. (See geologic map, pl. 1.)

The Tar Springs sandstone is a moderately fine-grained, yellowish-brown sandstone which occurs as uneven beds, most of which are thin. In this district the formation is characterized by carbonaceous fragmentary plant remains, which are especially abundant in the shaly beds that occur near the base and middle of the formation.

The thickness of the Tar Springs sandstone appears to be about 100 feet or slightly less.

[11] Weller, Stuart, and others, The geology of Hardin County, Ill.: Illinois Geol. Survey Bull. 41, p. 195, 1920.

Vienna limestone.—Overlying the Tar Springs sandstone in the block between faults 1 and 5 (see pl. 3) is a limestone whose lower part is thick-bedded, dark gray, and coarsely crystalline. This limestone weathers with dark-brown surfaces that appear much like the surface of a weathered sandstone. The upper beds of the limestone are dense and almost black, and they break with a sharp, chertlike fracture. Their weathered surfaces are dark greenish-brown, and pitted. The limestone is about 15 feet thick and probably corresponds to the Vienna limestone of the standard Chester section.

Waltersburg sandstone.—Overlying the Vienna limestone, and occurring in the same fault block is a thin-bedded, fine grained, shaly sandstone, which from its position in the section is thought to be the Waltersburg sandstone. It is from 15 to 20 feet thick.

Menard limestone.—Above the Waltersburg sandstone are beds of dense light-gray fossiliferous limestone that contain a large form of *Spirifer increbescens.* These beds weather with smooth brown surfaces. They dip steeply and contain numerous "gash" veins of calcite. Although they are not lithologically similar to the typical Menard limestone they have been mapped as Menard because of their containing large Spirifers that appear to be characteristic of the Menard limestone elsewhere.

Palestine sandstone.—No surface exposures of the Palestine sandstone were observed in the district, but the rock probably underlies the younger formations west of fault No. 4.

Clore limestone, Degonia sandstone, Kinkaid limestone.—The three uppermost formations of the Chester group occur along the escarpment in the block west of fault No. 4 and north of fault No. 5 (pl. 3). They are poorly exposed because of the covering of talus derived from the Caseyville sandstone, which crops out in the upper part of the escarpment. Because of the poor exposures as well as the thinness of both the Clore limestone and Degonia sandstone the three formations have been mapped as a unit.

The Clore, which consists of thin beds of limestone and shale, is probably covered in this area—at least no beds were seen which could definitely be correlated with it.

The Degonia sandstone consists of thin-bedded, fine-grained, yellowish-brown, shaly sandstone. Only two exposures of it were found, both in gullies along the escarpment, and its thickness could not be measured.

The Kinkaid consists largely of limestone with interbedded shales. The limestones are dense and dark gray, and weather with lighter-colored surfaces. In this respect they somewhat resemble the typical Menard limestone. Exposures of the Kinkaid limestone can be seen along the wagon road on the southward-facing escarpment at the western border of the mapped area, just north of the east end of fault No. 5.

The thickness of the Kinkaid limestone is variable because of the unconformity between it and the overlying Caseyville sandstone.

PENNSYLVANIAN SERIES

CASEYVILLE SANDSTONE

Resting unconformably upon the Kinkaid limestone there is a series of thick, massive beds of sandstone and conglomerate, with thinner shale beds, representing the Caseyville sandstone of the Pottsville group. These beds form the high cliffs along the escarpment in the northern part of the district. Much of the part of the formation that occurs in the area mapped consists of conglomerate beds.

STRUCTURAL GEOLOGY

The larger structural features of the Illinois-Kentucky field, and the relation of the Cave in Rock district to this field, are described on pages 5–10.

GENERAL ATTITUDE OF BEDS

The bedrock formations of the Cave in Rock district are nearly horizontal, except where local faulting has produced sharp flexures, known as "drags," in the wall blocks of the faults. Because the district lies on the north-northeast side of a broad domal uplift (see page 5) there is a general slight dip in that direction. In the southern part of Spar Mountain the average dip amounts to about 200 feet to the mile, or slightly more than 2°, and the average strike is about N. 80° W. In the north-central and northeastern parts of the district the average dip, apart from local relatively steep dips that may be the result of faulting, ranges from about 2° (185 feet to the mile) to about 3½° (320 feet to the mile), and the average strike is about N. 70° W. On Lead Hill the average strike is about N. 85° E., and the average dip is a little less than 2°.

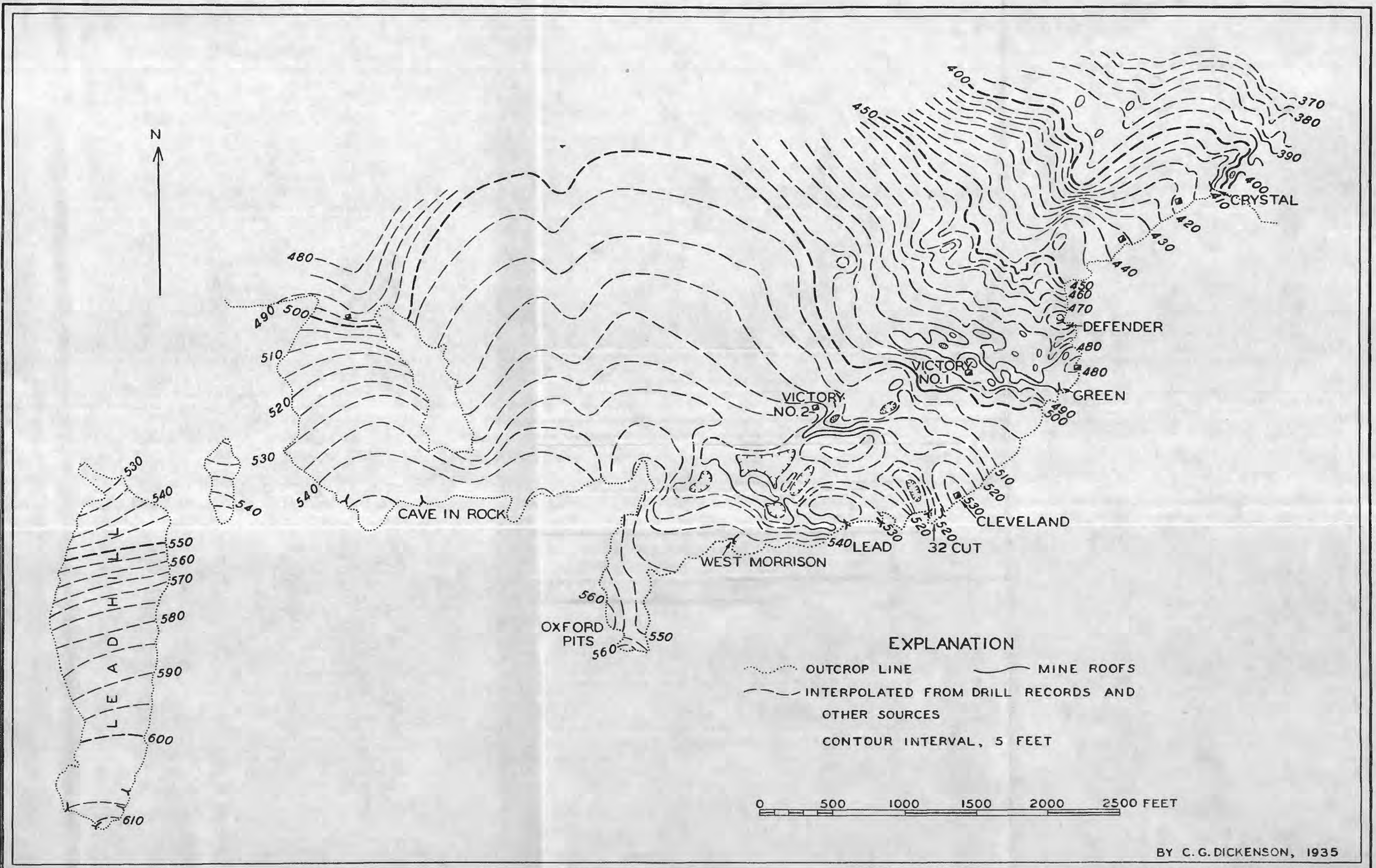
Because of this general northerly dip, the chief fluorspar horizon—the top of the Fredonia limestone—will be found at progressively lower altitudes north and northeast from the present productive area. At a point in the extreme northern part of the mapped area where the surface altitude is 600 feet, for example, the limestone would apparently be reached by drill holes or shafts at depths of 500 to 550 feet. Obviously the initial cost of mine development at such a point would be considerably greater than where the deposits are now being exploited. Nevertheless, deposits as rich as some that have been developed at shallower depths in the district could be mined profitably at depths appreciably greater than 500 feet.

FOLDS

There are no prominent or pronounced folds in the Cave in Rock district. The dips of the strata are the result partly of regional doming and partly of very minor, local folding. The broad doming of the Illinois-Kentucky field (see page 5) developed peripheral dips that range up to 20°, though rarely more than 15°, and northerly or northeasterly dips of this order of magnitude should not necessarily be interpreted as local structures. Such dips would be the normal result of the general doming, for the Cave in Rock district lies on the northeast flank of the dome. Northeasterly dips in excess of 20°, however, may commonly have some local structural significance, provided there is confirmatory evidence of local deformation. Dips in other directions than north or northeast, even though relatively low, may be highly significant, possibly as indicating local minor folds, but more probably as being related to local faulting. Such features are considered below in connection with minor faults.

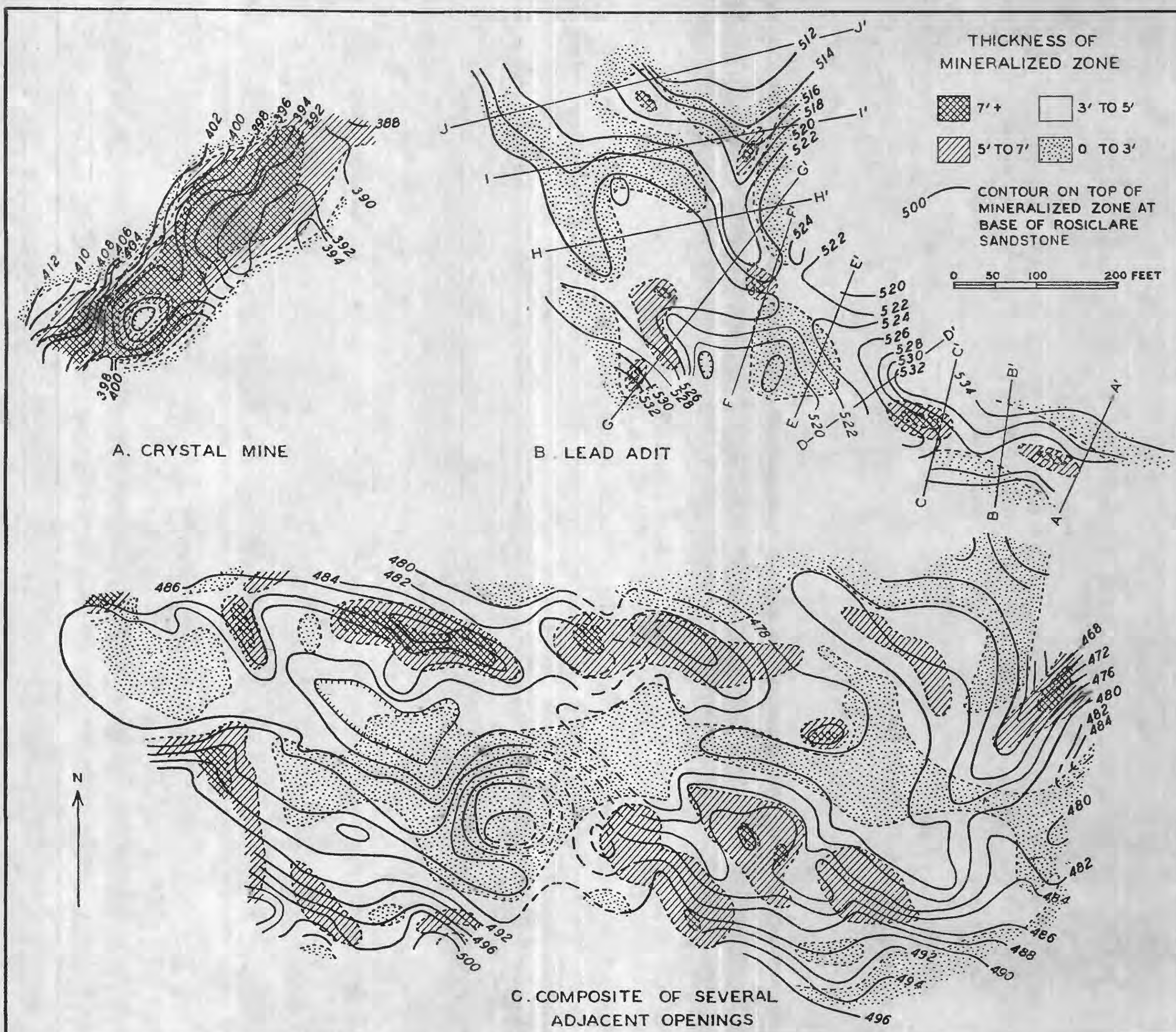
Small minor folds and gentle warpings, discernible in the mine openings, appear to follow definite directions, as if related to definite systems of fractures, and the degree of mineralization appears to be related in many places to such minor flexures. A general structural pattern that seems significant has emerged from the detailed mapping and contouring of the shale bed at the base of the Rosiclare sandstone. The details of these minor folds, and their apparent relations to fluorspar concentration, are described and discussed on pages 41–42. In general the axes of the minor folds may be grouped into two sets, one with axes striking N. 50° W. to N. 65° W., and the other with axes striking N. 40° E. to N. 50° E. Thus the first set, which is the more prominent of the two, is nearly normal to the Peters Creek fault zone and the second set is nearly parallel to this fault zone. These directions are also generally parallel to the trends of the minor fissures in the mines.

As minor folds or flexures, with associated fissures, seem clearly to have localized ore deposition—at least in some places—they should be important guides in prospecting for new ore bodies. But to discover them from surface indications is practically impossible because of the scarcity of good rock exposures in the mapped area, except along the Spar Mountain escarpment. For the most part only observations near the contact of the Fredonia limestone and Rosiclare sandstone would be of particular value, for in such places the stratigraphy is especially varied through a narrow range, and there is, moreover, reason to believe that many of the folds and minor fissures weaken or die out entirely in overlying formations. The Fredonia-Rosiclare contact lies deeply buried in most places north of the escarpment. Drilling to determine altitudes of this horizon and thus to contour it would ordinarily prove impracticable because of the generally small sizes of



CONTOUR MAP OF BASE OF ROSICLARE SANDSTONE MEMBER IN DEVELOPED AREA OF CAVE IN ROCK FLUORSPAR DISTRICT.

Interpreted from mine data, drill records, and surface exposures.



MAP SHOWING CONTOURS OF TOP OF MINERALIZED ZONE AND APPROXIMATE THICKNESS OF MINERALIZED ZONE IN SEVERAL MINES.

For profiles see figure 7.

the folds. A very close spacing of drill holes as well as very accurate measurements of depths to the key horizon would be necessary, and the procedure would be very costly.

Plate 4 presents an interpretation of the structure of the Rosiclare sandstone throughout the developed area, and plate 5 gives a more detailed contouring of the roof of the ore bodies in several of the mines.

JOINT SYSTEMS AND RELATED FRACTURES

Joints of the type commonly found in rock formations have not greatly influenced the localization of fluorspar in this area, except where, by their fortuitous occurrence in mineralized zones, they may have offered additional space and facility for the spread of solutions. In general, such fractures are discontinuous both horizontally and vertically, and many of them are restricted to certain beds or formations that are relatively brittle. Being everywhere present they have in many places, helped to prepare a terrain for the reception of mineralizing solutions, and it is easy to ascribe to them a greater importance than they deserve. However, where joint systems conform in orientation to regional axes or planes of deformation by folding and faulting, and display locally a closer spacing than elsewhere, they may deserve special attention from the prospector. Such prominent development of a joint system may, indeed, betoken a more direct connection with fissure zones of deeper origin, or with local folds. Exposures in Cave in Rock district are generally inadequate for displaying the connection of joints with important mineral bodies. In a few places, however, prominent joint systems are exposed, and in at least two localities in the undeveloped part of the district they are not only in belts of possible minor faulting, but their strikes of N. 50° E. and N. 60° E., respectively, coincide approximately with one of the major structural trends of the region. These localities are on the larger tributaries of the prominent creek valley in the northeastern part of the mapped area.

Minor fissures of little or no displacement are commonly found in the mines, and in such relations with mineral bodies and local structures as to indicate a close genetic connection with them. These fissures, filled with fluorspar, appear as veins in the roofs of drifts and in several of the workings. They have been regarded as "leaders" in underground exploration and development. Their structural significance and relations to ore bodies are discussed in some detail in a succeeding section (page 45). In general, these fissures are narrow cracks, usually not more than an inch wide, and may be remarkably persistent. They probably are tension cracks formed by local warping, and in part at least trend parallel to the axes of the minor folds with which they may be connected. Many of these fissures probably belong to a system trending from N. 45° E. to N. 60° E., average about N. 50°E. These trends correspond to those of the minor folds whose axes range from N. 40° E. to N. 50° E. (See page 22.) Several fissures not belonging to this set were measured, and their trends are N. 47° W. to N. 85° W. There is generally no appreciable displacement along these "roof cracks," but some of them may be directly over very minor fault fissures that penetrate through the floor to the ore horizon.

FAULTS

PETERS CREEK MAJOR FAULT ZONE

The Peters Creek fault zone has been described by Weller[12] and appears on his geologic map of Hardin County. That portion of the zone that borders the Cave in Rock district has been mapped on a larger scale and in greater detail, and appears on the geologic map accompanying this report (pl. 3).

The Peters Creek fault zone is one of the major structural features of the Illinois fluorspar field, and has been traced for about 11 miles, from the Ohio River nearly to the Saline River. The general strike of the fault zone is N. 45° to 50° E. Through the northeast third of the zone it consists of a single major fault. At a point in the north-central part of Cave in Rock district, the single fault passes southwestward into a fault zone comprising three major faults and at least three minor cross faults. The larger scale of the base map used for this report has permitted a closer identification and mapping of details than was possible at the time of Mr. Weller's field work. This mapping and the resistivity profiles (pl. 21) show that the northern part of the area is deformed by minor faults, which probably are connected with the Peters Creek fault zone.

Regarding the faults of the Peters Creek zone, Weller says "the downthrow is on the north side of each of these faults and the accumulated effect north of Peters Creek is a downthrow of 1,000 feet or more, nearly the full thickness of the Chester group." In the portion of the fault zone bordering the Cave in Rock district the aggregate displacement is about 500 feet. The stratigraphic details are shown on the geologic map (pl. 3), and detailed descriptions of the individual faults of the zone, as they occur in the mapped areas are given below.

Some prospecting has been done along the Peters Creek fault zone, particularly at the F. E. Martin and the Eureka prospects, about 1½ miles northeast of the mapped area, where shallow shafts have revealed a small vein containing fluorspar, calcite, a little sphalerite and galena, and a very little chalcopyrite. These prospects are on the part of the fault zone that apparently consists of a single break. Prospects on the zone within the mapped area have given no evidence of important

[12] Weller, Stuart, and others, The geology of Hardin County, Ill.: Illinois Geol. Survey Bull. 41, 1920.

mineralization, but along this part of the zone, except for a short strip north and northwest of Lead Hill, the wall rocks at the surface are composed almost entirely of sandstone and shale belonging to the Chester group and the Caseyville conglomerate. Such formations are notably less favorable to prospecting, in general, than the lower, thick limestones. North and northwest of Lead Hill the southeast wall consists of Fredonia limestone at the surface, but the low, flat sink-hole character of the area and the thick residual clay mantle are greatly obscuring features. Also, for a short distance along the course of the easternmost fault of the zone the Peters Creek valley has an exceptionally thick cover of alluvium, in which there would be no evidence of a subjacent vein. Farther southwest the fault zone enters an extensive area of Fredonia limestone, in which the stratigraphy and lithology should be favorable for prospecting, but in which the surface mantle is thick and obscuring. In this area prospecting is apt to be expensive.

DESCRIPTIONS OF FAULTS

By O. E. Wagner, Jr.

For convenience of treatment the individual faults shown on the geologic map, plate 3, have been numbered F1, F2, etc., and the following brief descriptions are correspondingly designated. Faults 1, 2, 3, and 4 comprise the principal faults of the Peters Creek fault zone within the mapped area, and faults 5 to 17 inclusive are minor faults.

Fault 1.—An excellent exposure of the northwesternmost fault of the Peters Creek fault zone, called No. 1, can be seen in the west bank of Peters Creek near the southwest corner of the district, at a bend where the creek is cutting this bank. At one place the fault plane is exposed and the sandstone to the east has been brecciated and altered to quartzite, a rock which is more resistant to erosion than the other rocks of the area and forms prominent bluffs and ridges nearby, known locally as "reefs." The strike of the fault here is N. 55° E. and its dip is steeply to the northwest. The footwall, on the southeast side, consists of Cypress sandstone, and the hanging wall is probably of Hardinsburg sandstone, so that the displacement is about 200 to 300 feet.

About 500 feet upstream from this exposure a steeply dipping quartzite with quartz veinlets is exposed. The bedding strikes N. 50° E. and dips to the northwest. About 3,000 feet farther upstream another good exposure of this fault is to be seen on a northwestward-flowing creek which crosses the fault plane. The outcrop shows a gray shale that strikes N. 10° E. and dips 80° NW. The shale dips under Tar Springs sandstone and is thought to belong to one of the shale beds within that formation. The rock at the surface on the southeast or hanging-wall side of the fault is probably Tar Springs sandstone, supposedly brought up on a cross fault—designated on plate 3 as fault 6—which has taken up most of the displacement.

Fault 2.—Fault 2, southeast of fault 1, can be traced with reasonable certainty southwestward from an old prospect shaft, located on the actual fault plane near its northeast end, to a point just southwest of a cross fault, No. 7. Between these points its course is marked by outcrops of quartzite, by slickensides, and by exposures of steeply dipping rocks; farther to the southwest its course is inferred from the character of the topography and from the areal distribution of the strata. The displacement northeast of fault 7 appears to be from 300 to 400 feet, but is reduced at fault 7 to about 100 feet.

Fault 3.—Fairly good exposures of brecciated quartzite with quartz veins and of brecciated limestone with calcite veins can be seen along fault 3 near its northeast end, where its displacement is estimated to be about 200 feet, but to the southwest the displacement becomes smaller and breccia less common. Along most of the length of the fault the displacement is from 50 to 100 feet. Southwest of fault 7 the position of fault 3 is mapped on the basis of topography and stratigraphy, except on the ridge at the southwest end, where there are good exposures of quartzite.

Fault 4.—Faults 1, 2, and 3 converge within a short distance and the Peters Creek fault zone is represented to the northeast by what is called fault 4. This may be a zone of closely spaced faults, rather than a single fault. The displacement on fault 4 is estimated to be about 600 feet at its southwest end, but it gradually diminished northeastward. No exposure of the actual fault plane has been found because the talus along the escarpment forms a cover that obscures the actual position and character of the fault trace or traces, but the course of the fault is marked by the presence of abundant quartzitic and brecciated material.

Fault 5.—Fault 5 is a cross fault trending westward from about the middle of the Peters Creek zone to a major fault of northeasterly strike outside the mapped area. It is one of the most difficult to trace because of the similarity of the limestones in the two walls, but steeply dipping beds and exposures of brecciated limestones veined with calcite are found along its course.

Faults 6 and 7.—Two cross faults, numbered 6 and 7, are inferred from the stratigraphy and dips of the nearby rocks, but their locations and strikes have been only roughly determined.

Fault 8.—Evidences of fracturing observed at a shallow prospect shaft on the saddle northeast of Lead Hill are believed to indicate a minor break which is mapped as fault 8. The evidence for appreciable displacement and the exact position of the fault are uncertain.

Fault 9.—Near the old shaft in the valley northeast of Lead Hill there are indications of a fault within the Fredonia limestone. This fault, indicated as fault 9, is of undetermined, but probably small, displacement, and has a strike of N. 60° E. The limestone near the fault has been replaced by quartz to form a solid mass of gray quartzite. Limestone on the dump pile beside the shaft contains both fluorspar and galena.

Fault 10.—In the lower working of the old Cave in Rock mine there is a zone of brecciated limestone containing fluorspar and a relatively large quantity of galena. Some of the limestone has been replaced by quartz to form quartzite. A fault striking about N. 20° W. is believed to pass through this zone, and is mapped as fault 10.

Fault 11.—Fault 11, which has a strike of N. 55° E., is encountered in an adit penetrating the Levias limestone. It is revealed by the displacement of a bed of shale within this limestone, the shale being 3 feet lower on the west side of the adit than on the east. Fissure veins of fluorspar in the limestone nearby all strike parallel to the fault.

Several of the prospects near this fault show bedding-replacement deposits of fluorspar in the Levias limestone and in limestone of the Renault formation.

Fault 12.—The evidence for fault 12 consists in a slight displacement of the base of the Rosiclare sandstone, together with the discovery of a fragment of slickensided sandstone in the gully through which the fault is thought to pass. The displacement, as indicated by the difference of altitude of the base of the Rosiclare sandstone on each side of the gully, is about 10 feet. The downthrow is on the east, but the exact strike of the fault could not be determined.

Fault 13.—A fault with horizontal displacement and a strike of N. 70° W. is said to be crossed by the old adit just east of the plant of the Benzon Fluorspar Co. The limestone east of the adit has prominent fissures, 1 to 3 inches wide, filled with fluorspar, and strikes N. 70° W. and N. 40° E.

Fault 14.—In the workings of the Victory Fluorspar Co.'s mine No. 1 there is a postmineralization fault of horizontal displacement. The fault is nearly vertical and strikes N. 70° E.

Fault 15.—The workings of the Crystal mine reveal a postmineralization fault of small displacement, striking N. 55° E. A vein of barite, as much as 6 inches in width, extends along this fault.

Fault 16.—Fault 16 is considered to be one of the most important minor faults in the area. It is best exposed in the creek a quarter of a mile north of the Crystal mine. Here the Paint Creek shale on the foot-wall side is dragged along the fault plane so that it dips steeply to the southeast and the Bethel sandstone on the hanging-wall side has been distorted and altered to quartzite. In the quartzite along the fault plane sphalerite, chalcopyrite, and greenockite were found.

Fault 17.—The mapping of fault 17 is based on rather doubtful evidence. Where the fault supposedly crosses the creek bed at this locality, Cypress sandstone is exposed. The sandstone beds are considerably distorted and there are prominent joints with a strike of N. 50° E.

PREVIOUS INTERPRETATIONS OF FAULTING

In previous publications, as noted below, two faults have been inferred for which the present investigation has yielded no decisive evidence.

Bain's report [13] records a fault of east-by-south trend at the foot of the south escarpment of Spar Mountain. The topographic pattern here is somewhat suggestive of a fault zone, but there is no stratigraphic evidence of its existence. The vertical displacement along a fault here could not be more than a few feet, probably 20 to 30 feet at the most, to judge from the altitudes of the Rosiclare sandstone—a good horizon marker—as exposed in Lead Hill and in the southern face of Spar Mountain.

Schwerin [14] describes a fault, which he calls the McWade fault, as extending eastward from the Peters Creek fault zone across the north end of Lead Hill, through the old Cave in Rock mine, thence northeastward to the top of Spar Mountain, thence northward through the prominent sinkhole to the Peters Creek fault zone in the northern part of the mapped area. At several places along this course there are undoubted evidences of minor faulting, but that these points lie on a single and continuous fault was not demonstrated by the present work. Certain of the underground evidence cited by Schwerin, however, was not accessible at the time of the investigation. That more minor faults exist in the area than are indicated by field data at hand seems very probable, but such faults could be disclosed only by underground development. Theoretically, however, if faulting has occurred along the course indicated by Schwerin, it is probably represented by intersecting breaks, rather than by a single broadly curved fault, and probably one of these breaks follows a course similar to that suggested earlier by Bain. The apparently unbroken continuity of the Rosiclare sandstone in the narrow southward-extending promontory of Spar Mountain, where the Oxford open pits are situated, argues against the presence of an east-west fault through the promontory. If there is such a fault, certainly the displacement—either vertical or horizontal—must be very slight. To prove that a "McWade fault" exists, and crosses Spar Mountain, and to trace its course, would require extensive underground exploration, or accurate stratigraphic measurement of numerous drill holes. Such a fault, if it exists, might have considerable economic importance.

---

13 Bain, H. F., Fluorspar deposits of southern Illinois: U. S. Geol. Survey bull. 255, p. 54, 1905.

14 Schwerin, Martin, An unusual fluorspar deposit: Eng. and Min. Jour., vol. 126, No. 9 (Sept. 1, 1928), p. 335.

GEOPHYSICAL EVIDENCES OF FAULTING

As a part of the cooperative project comprising a comprehensive study of the Cave in Rock district, M. King Hubbert of the State Geological Survey made 30 geophysical traverses across the district, excepting Lead Hill and most of the sinkhole area. The traverses were run both parallel and perpendicular to the Peters Creek fault zone and were as nearly equally spaced as topography would permit. The details, results, and interpretations of this work are presented in part 2 of this volume. It should be pointed out here, however, that several resistivity breaks found in different parts of the area where surface evidence of faults is wanting, particularly in the north-central and northeastern parts, indicate the probability that these parts of the area are also probably deformed by minor faulting.

TOPOGRAPHIC EVIDENCES OF FAULTING EAST OF MAPPED AREA

The topographic form of the long, straight escarpment extending southeasterly from the prominent creek valley on the eastern edge of the mapped area suggests that it may have been formed by faulting, but it was not possible to extend the mapping and detailed field studies to include this area. The trend of the escarpment is such that it could have been determined by normal processes of erosion, because it is essentially parallel with the strikes of the beds that are exposed in the escarpment, but the shape and extent of the adjacent area of Fredonia limestone, southwest of the escarpment, suggests also a downfaulted block. Faulting along this escarpment might be of considerable importance in prospecting. However, fluorspar deposits are not known to exist along it although a small amount of prospecting has been done at a few points. The Rosiclare sandstone is exposed along the escarpment, and it has the usual general northeast dip, but there is no obvious discrepancy in altitudes between its outcrop here and the exposure of the same horizon along the east side of Spar Mountain. Moreover, the sandstone belts along both escarpments join in the creek valley to the north without apparent displacement, hence any faulting at the base of the southeasterly trending escarpment must have very small displacement unless the sinkhole area between them is part of a downfaulted block. Again, the presence of "sub-Rosiclare sandstone" as the capping of a knoll in the lowlands, within the mapped area, precludes the possibility of much displacement of the western part of such a block.

It is perhaps pertinent to call attention at this point to the presence of a bedding deposit in the sinkhole area, about three-fourths of a mile northeast of the village of Cave in Rock, and about the same distance from the southeastern part of the escarpment. This deposit (prospected in 1917) is at a much lower horizon than the Spar Mountain deposits, being near the base of the Fredonia limestone, but it appears to be similar in structure and texture, and its presence here demonstrates the fact that mineralizing solutions have risen along minor fractures far outside of the mapped area.

FLUORSPAR DEPOSITS OF THE DISTRICT

GENERAL STATEMENT

The economic fluorspar deposits of the Cave in Rock district are elongated tabular or lenticular bodies that clearly have replaced certain beds of the thick Ste. Genevieve limestone. They are here called "bedding-replacement deposits," or "bedding deposits," for reasons discussed on page 8. Several distinctive features indicate that the stratigraphic, lithologic, and structural conditions controlling the formation of these deposits differ from those that governed the deposition of the vein deposits elsewhere in the field, although the sources of the mineralizing solutions and the time of formation were the same.

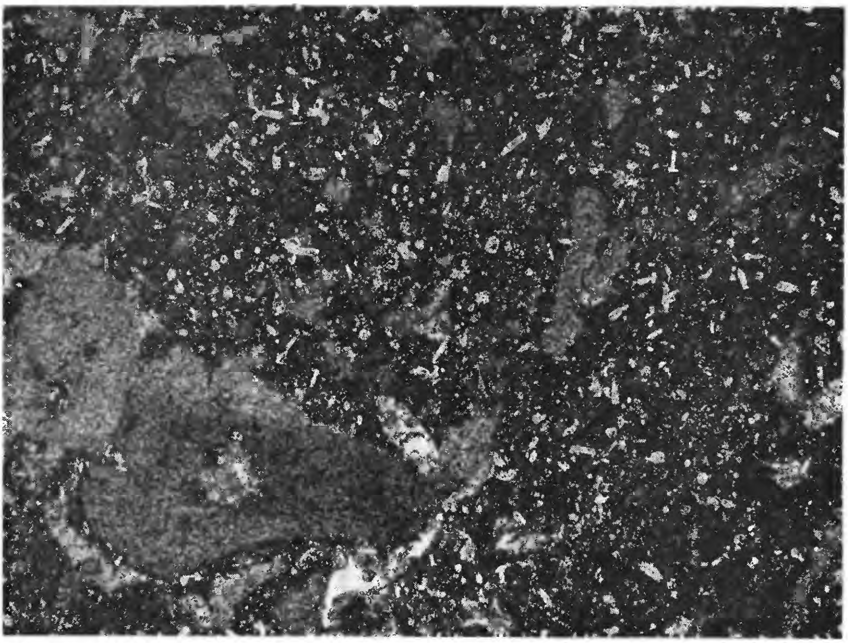
The distinguishing features of these deposits are (1) they occur at certain stratigraphic horizons of which one in particular—the top of the Fredonia limestone—has so far proved to be of particular importance; (2) they replace the host limestone along its bedding planes and preserve the coarser textural features of stratification and cross bedding; (3) they were deposited in readily replaceable horizons beneath dense, unreplaceable beds that form a well defined cap rock; (4) their localization was favored by local very minor folds or flexures; (5) they were deposited by solutions that penetrated laterally from minor fissures of little or no displacement, which, in turn, were greatly constricted in passing upward into the dense shale cap rock or that failed entirely to penetrate the cap rock; (6) their mode of replacement resulted in the development of characteristically layered ores, generally called "coon-tail spar"—the layers marking stratification planes and cross-bedding laminae; (7) they are not connected with veins of commercial size.

The mode of occurrence and the form of the bedding-replacement deposits permit comparatively simple methods of mining and milling, and together with the high quality of much of the ore give them a distinct advantage over many of the vein deposits.

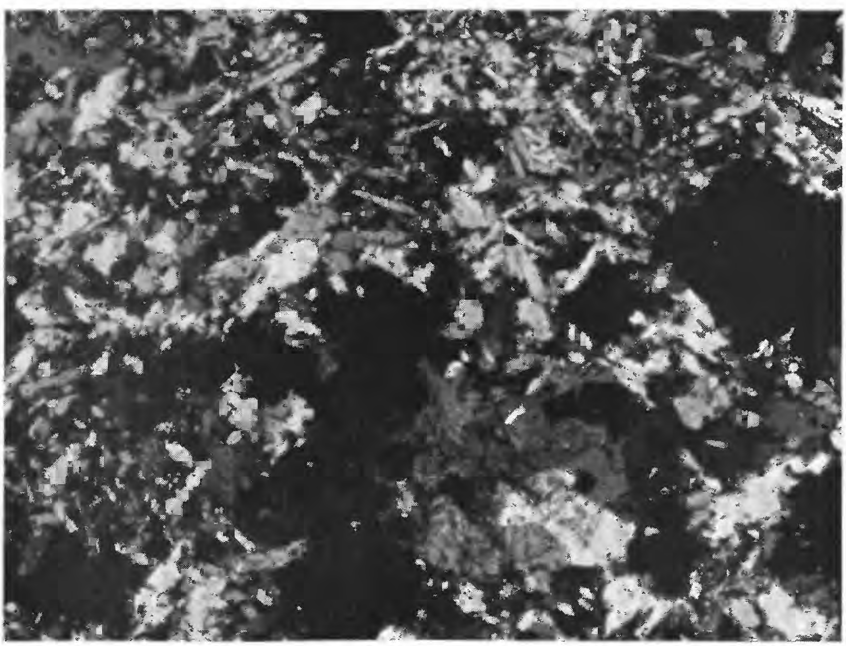
MINERALS OF THE DEPOSITS

The mineral composition of the bedding-replacement deposits is comparatively simple and resembles that of the vein deposits except that sulfides are much less abundant and more localized[15] in the bedding-replacement deposits than in the veins. The minerals present in the deposit are fluorite (fluorspar), calcite, quartz, barite, galena, sphalerite, chalcopyrite, marcasite, smithsonite, and cerussite, all of which were introduced after formation of the host rocks, and a

[15] See addendum, page 71.

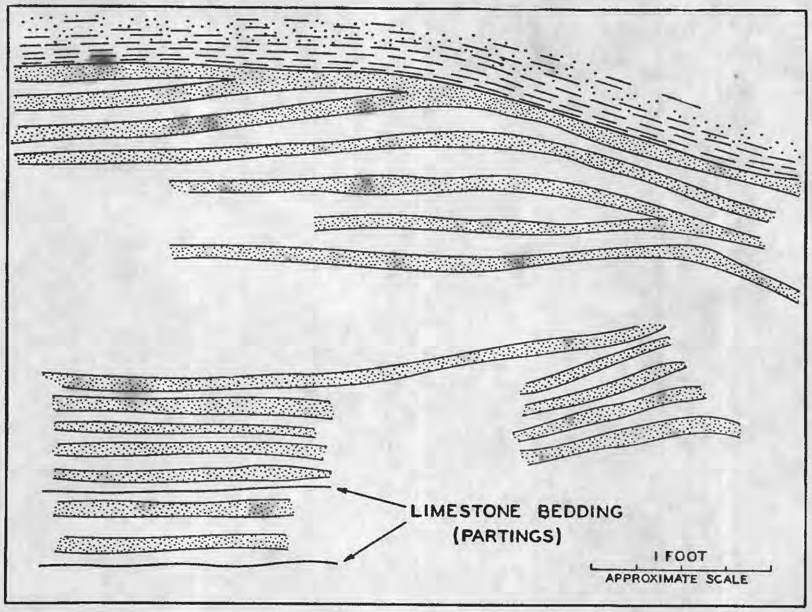


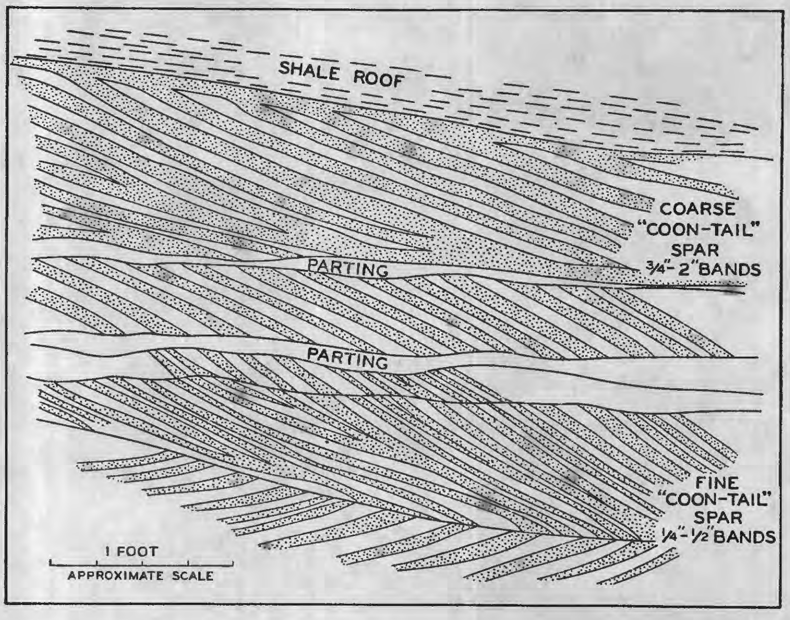
A. PHOTOMICROGRAPH OF LIMESTONE SHOWING MICROSCOPIC QUARTZ CRYSTALS.

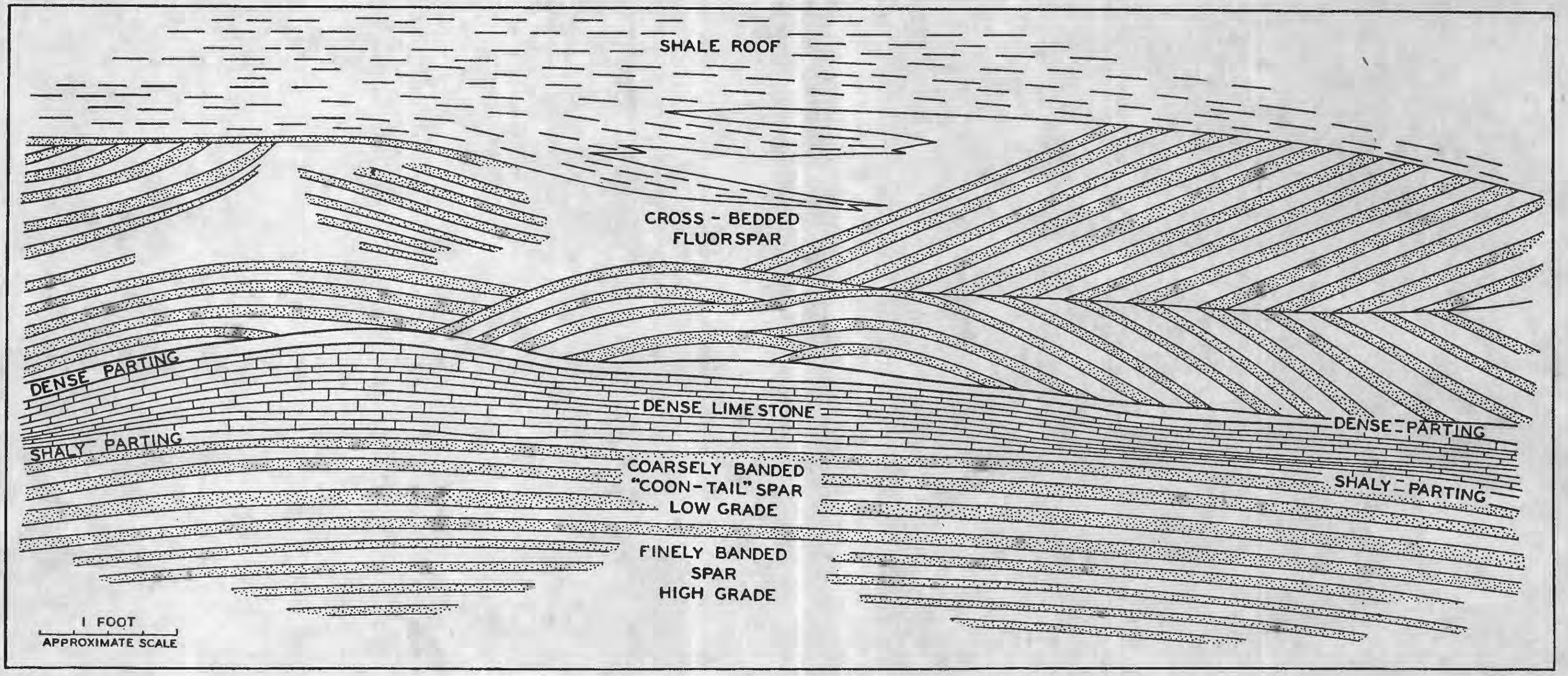


B. PHOTOMICROGRAPH OF FINE-GRAINED SILICEOUS BAND IN ORE SPECIMEN FROM CAVE IN ROCK MINE.

SPECIMEN OF SILICEOUS MATERIAL FROM WASTE PILE OF CAVE IN ROCK MINE.







SKETCHES OF PARTS OF FACES IN MINES ON SPAR MOUNTAIN.

Show alternating bands of pure (shaded) and impure (unshaded) fluorspar, attitude of bands, and bedding and cross-bedding structure of fluorspar ore.

ferriferous carbonate (probably ankerite) that was probably an original constituent of some of the limestone layers and which is observable in the more impure layers of the ores, where it has apparently escaped complete replacement.

Fluorite.—The chief mineral of the deposits is fluorite (commercial name fluorspar). This mineral is much more coarsely crystalline in the purer layers of ore than in the less pure, siliceous or ferriferous layers. In large vugs and cavities, the majority of which appear to occur chiefly at the tops of ore bodies, just below the roof rock, exceptionally large crystals are common; some of these crystals measure more than 6 inches across the crystal faces. Fluorite generally crystallizes as simple cubes, and this is the prevailing form in these deposits also, but occasionally druses or large aggregates are found that display well developed dodecahedral faces modifying the edges of the dominant cube forms.

The fluorite ranges in color from colorless or white to various shades of amber, deep purple, violet, lavender, and blue. Large crystals attached to the walls of cavities commonly have an amber to colorless core and a purple shell, the two being sharply distinct. A similar color zoning is found also in the "combs" of coarser grains that make up the purer layers of the "coon-tail" spar. Amber and purple hues are more common than lavender and violet, and the blue and greenish-blue shades are exceptional. The strong hydrocarbon odor obtained by breaking the purple variety suggests that its color is due to organic material, and the fact that purple fluorite bleaches out to pale shades when exposed to sunlight, as in dump piles, lends some support to this hypothesis. The blue and violet hues may, however, be due to the presence of metallic ions in the mineral, as some crystals of nearly colorless fluorite have been found in which halos of these colors surround inclusions of chalcopyrite. Small inclusions of pyrite and marcasite, on the other hand, have no colored halos. Comb structure is common in the pure layers of the ores (see below), and the relatively coarse-grained fluorite of a pure layer is marked by deeply colored material along the center of the layer; this colored portion is crystallographically continuous with the less strongly colored material—commonly amber or colorless—above and below.

Calcite ("calc"; "calcspar").—Calcite is not particularly prominent throughout the bedding-replacement deposits, although it is an abundant mineral of the vein deposits and predominates in some parts of the veins. In part it occurs as small grains in the less pure bands of the ores, where replacement has been incomplete. To a large extent however, the carbonate grains of these layers are a ferriferous variety —perhaps ankerite—instead of the pure calcium carbonate that forms the mineral calcite. Coarsely crystalline white calcite is locally abundant where it has crystallized in cavities and brecciated zones, as it has done near fissures, particularly just beneath the roof rock. Some of these crystals are several inches in diameter and the masses are similar in appearance to the typical coarse calcite of the vein deposits.

A later generation of calcite is represented by well-formed crystals that were deposited upon crystals and drusy surfaces of fluorite in open spaces. Doubly terminated complex crystals of the mineral may be found in this situation. The crystals range from minute sizes up to several inches in length, and are mostly transparent or translucent, and colorless to buff-colored.

Barite (barytes; "heavy spar")—Barite is present at a few places, but is to be considered a very minor constituent of the deposits, and consequently is not of economic importance. It appears in vugs, cavities, and locally disturbed zones, generally in the upper parts of the deposits, and is practically entirely absent from the more massive, and compact, "banded" portions of the ore deposits. Apparently it is a mineral of relatively late development.

An excellent description of the mineral and its paragenetic relationships has been given by Bastin,[16] who regards it as a late secondary mineral replacing fluorite, calcite, and limestone.

Quartz.—This mineral is generally present in the deposits, but in most of the developed fluorspar bodies it occurs so sparingly that simple milling will easily give a product that satisfies the commercial requirements. On the other hand, at a few places, the deposits obviously contain so much quartz that a satisfactory product cannot be obtained by the milling methods in use.

Minute prismatic crystals of quartz are disseminated in the oolitic limestone occurring in the ore bodies chiefly in the impure layers. Plate 6, *A*, is a photomicrograph showing quartz crystals in material from the bedding-replacement deposits. To some extent these crystals probably represent silica transported in fluoriferous solutions, but some of it, especially in the impure layers, may well have recrystallized during the mineralizing epoch. Quite similar quartz crystals appear in the wall rocks of the vein deposits at some places, as in the "jasperoid" of the Mary Belle mine in Kentucky.[17]

A third mode of occurrence is illustrated by specimens obtained from some dump material at the old Cave in Rock mine and from certain prospects on the east side of Lead Hill. These specimens show alternate layers of pure crystalline fluorspar and quartz. In one the quartz layers are composed of well-formed crystals arranged in comb structure; in other specimens (see pl. 7) layers of crystalline purple fluorspar alternate with fine-grained layers of quartz. Under

[16] Bastin, E. S., The fluorspar deposits of Hardin and Pope Counties, Ill.: Illinois Geol. Survey Bull. 58, pp. 60-62, 1931.

[17] Currier, L. W., Fluorspar deposits of Kentucky: Kentucky Geol. Survey, ser. 6, vol. 13, pp. 18, 70, 92, 95, 1923.

the microscope the quartz layers are seen to be clearly made up of quartz that has replaced the matrix, partly as perfect crystals, partly as elongated "feathery" crystals, and partly as fine-grained "matted" aggregates of nearly chalcedonic texture (see pl. 6, *B*). Some of the grains have outlines that suggest original clastic texture modified slightly by recrystallization. Many of the grains and crystals attributed to replacement show included patches and bands of minute calcite grains, and many of these bands are parallel with the crystal faces of the quartz grains that include them.

A fourth mode of occurrence of quartz is that of drusy surfaces of crystals upon the faces of fluorspar crystals. This quartz apparently belongs to a relatively late epoch of deposition.

Galena.—The primary sulfide of lead, galena, is not abundant in most of the bedding-replacement deposits, though it is prominent in many of the vein deposits elsewhere in the field. Where found it is well crystallized, and appears within and upon the layers of relatively coarsely crystalline fluorspar, where it is intergrown with the fluorspar or else occurs as crystals upon fluorspar crystals. It has been found particularly at the old Cave in Rock mine, and at the C. M. Miller mine on the west side of Lead Hill. It was deposited relatively late in the mineralizing epoch, and hence was both contemporaneous with fluorspar and later.

Sphalerite (zinc blende).—Only a few crystals of sphalerite were noted in the deposits that were studied[18] though the mineral is quite common in the vein deposits of the Illinois-Kentucky field and in some of the veins it constitutes recoverable ore bodies. Vein relations indicate that, like galena, it was deposited relatively late in the mineralizing epoch.

Chalcopyrite and marcasite.—Chalcopyrite and marcasite occur in very small quantity as minute crystal inclusions in fluorspar. In the large crystals of fluorspar—that show them best—these sulfides are restricted to the outer zones of the host mineral, as if their deposition had begun later than that of the fluorspar and had continued while fluorspar was still being deposited. The relation of colored halos to chalcopyrite inclusions has been mentioned (p. 31).

Cerussite and smithsonite.—The carbonates of lead (cerussite) and of zinc (smithsonite) have been observed in some of the deposits. The variety of smithsonite that is known, from its color and appearance, as "turkey-fat" has been found at Lead Hill as a coating on fluorspar crystals.

TEXTURE OF THE DEPOSITS

The fluorspar deposits of the Cave in Rock district show a well developed and characteristic layering, which gives a markedly banded

[18] Local concentrations of sphalerite in the Cave in Rock district have been reported since this report was written; see addendum, page 71.

appearance to exposed surfaces. From a study of the ores, the unreplaced limestone of the ore horizon, and the structures of the beds, it is believed that the ore layers reflect original stratification and cross bedding of the host rocks. The reasons for this belief are discussed below.

The typical ore consists of alternate layers of pure, coarsely crystalline fluorspar, and relatively impure fine-grained material that is, however, dominantly fluorspar. The layers range in thickness from a small fraction of an inch to several inches, mostly from ½ inch to 1 inch. In places the layers are remarkably continuous, and uniform in thickness; in others they are short and bifurcated, and are also truncated by roof or floor beds or by other groups of bands. The pattern of the layers clearly simulates the cross-bedded structure of the host rock (see pl. 8).

A noteworthy feature of the coarser fluorspar layers is their prevalent crustification and comb structure formed by crystals that project toward the central zones of the layers, which are generally marked by vugs (see pl. 9). This structure shows that crystals of fluorspar grew from the outer borders of the pure layers toward their centers, but not quite filling the space originally occupied by rock material. Such crustification is common in veins formed by deposition in open fissures; it is inconceivable, however, that closely spaced and extensive horizontal open fissures could have existed here and the comb structure is therefore attributed to progressive replacement. The zone of vugs may be centrally situated within the layer or it may be closer to one side than to the other (see pls. 10, *A*, 11), but it is nearly always recognizable from the presence of open spaces and also from a deeper coloration of the fluorspar bordering the vugs (see pl. 9).

In some of the ore the pure layers have few vugs and are colorless, but show a line of contact between the crystals from the two walls of each layer (see pl. 11). Some of the ore breaks readily along the vug lines, exposing surfaces of well-formed crystals (see pl. 9). A specimen from the east side of Lead Hill showed druses of quartz crystals in comb structure between each two layers of purple fluorite crystals, with the vug zones between the quartz layers; in these the fluorite layers were fine-grained and somewhat impure. Another specimen showed layers of similarly crustified quartz crystals alternating with layers of clear, coarsely-crystalline, purple fluorite.

The less pure layers in the ores consist of relatively fine grains of fluorite, carbonates, and in some layers quartz. Such layers show no comb structures or crustification. They are generally gray or brown and somewhat resemble original rock material, not only in color, but also in texture. Even the stratification caused by variations in the original texture and composition of the rock is clearly apparent in some of these layers. In several specimens collected at the Cave in

Rock mine such layers contained fossil shells and oolites that had been partly replaced by fluorite.

Plate 10, *B*, shows differences in texture and composition, as well as the lack of sharpness in the contact between the coarse and fine-grained layers. Most of the impure layers contain unreplaced carbonates. Some of this is calcite but much of it consists of small rhombs of a ferriferous carbonate—ankeritic or sideritic calcite—as indicated by the indices of refraction and by the strong yellow-brown color of the weathered material. Under the microscope these grains commonly show outer zones that are stained brown with limonite, and some limonite extends into the grains along cleavage cracks (see pl. 12, *B*). A difference in sharpness between the two contacts of an impure layer with adjacent pure layers (see pls. 10, *A*, 11) reflects original variations of texture and composition in the original limestone.

A study of several thin sections shows that most of the minute secondary quartz crystals found in the Cave in Rock ores occur in the relatively impure layers, and a condition that also reflects differences in composition of the original rock layers.

The range in fluorspar content of the less pure, fine-grained layers is variable within wide limits; some of these layers contain as much as 90 percent of CaF_2 but in general their fluorspar content is much less and even in the highest grade ores probably averages less than 80 percent. These layers are not separated in milling the ores, however, and for much of the richer ore taken out the requirements for metallurgical spar of 85 percent of CaF_2 and not over 5 percent of silica were met with very little milling of the ore. Toward the limits of the ore bodies, on the other hand, the average fluorspar content decreased so that marginal ores requiring carefully controlled milling were mined in places. It has also been the practice to mix such marginal ores with richer material from other parts of the ore bodies in order to obtain a product of standard specifications. The lateral boundaries of the ore bodies are thus economic in large part rather than structural, but the upper and lower boundaries are more apt to be stratigraphic and structural boundaries.

Specimens collected from the dumps at the lower adit of the Cave in Rock mine, and at the Miller mine on the west side of Lead Hill, consist of alternate layers of coarsely crystalline fluorspar, showing the usual crustification, and fine-grained, slightly porous quartzite. Thin sections of the quartzite reveal a texture that indicates replacement of impure limestone or calcareous sandstone by quartz. In general the grains of this quartz are interlocking, elongated, "feathery" edged, or sharply euhedral, rather than rounded like sand grains (see pl. 6, *B*). The faces of the fluorspar crystals of the other layers are commonly coated with druses of quartz crystals.

PARAGENESIS OF THE DEPOSITS

The order of deposition of the several minerals in the bedding deposits appears to be generally consistent with the interpretations applied to the vein deposits, as presented in the writer's earlier report on the Illinois fluorspar field.[19] The assemblage of minerals is the same as in the veins, but prominent amounts of course vein calcite are lacking in the bedding-replacement deposits, and consequently the replacement relation between fluorite and calcite, so obvious in the veins, is not clearly displayed. The paragenetic relations of quartz, also, are more complex in the bedding-replacement deposits than in the veins.

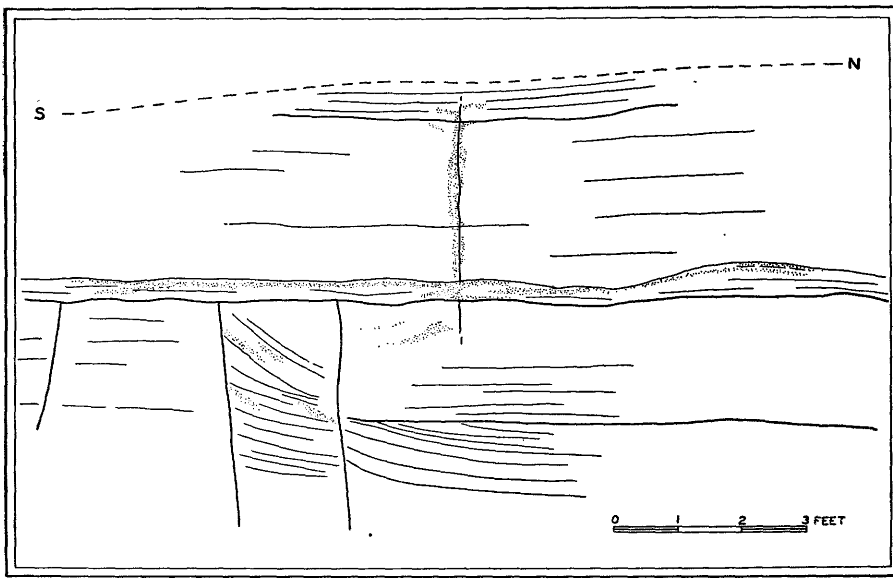


FIGURE 4.—Sketch of exposure at prospect on east side of Lead Hill showing incipient mineralization along joints and bedding planes. Stippling indicates fluorspar, light lines indicate bedding and cross bedding of limestone, and heavy lines indicate joints.

FLUORSPAR

The fluorspar of the Cave in Rock deposits clearly replaces carbonate grains, oolites, and the fine-grained calcareous matrix of the limestone country rock. Pseudomorphs of oolites and fossil fragments may be observed. In many places it is clearly seen that the mineral follows stratification planes and layers of the host limestone, extending as replacement layers or streaks from small cross-cutting fractures. (See fig. 4.) In general, the writer believes that the characteristic layering of the fluorspar bodies is due primarily to replacement of

[19] Currier, L. W., Fluorspar, lead, and zinc, in Weller, Stuart, and others, The geology of Hardin County, Ill.: Illinois Geol. Survey Bull. 41, pp. 257-260.

bedding and cross-bedding layers. This matter is discussed further in the subsequent section dealing with origin of the deposits.

In some weathered exposures of the unmineralized Fredonia limestone at the ore horizon, layers of relatively pure calcitic material alternate with layers of less pure, ferriferous carbonate that are made prominent by oxidation of the iron content, so that the rock surface shows a series of alternating gray and brown bands. In places of light or moderate mineralization irregular layers of clear, pure, crystalline fluorite alternate with impure ferriferous layers in which brown carbonate rhombs are abundantly disseminated (see pls. 10, *B*, 12, *A*). Contacts between the layers are in part quite sharp, and in part gradational. It is inferred that the iron-bearing carbonate material was less readily acted upon by fluorine to form calcium fluoride than was the pure calcitic material. The fluorspar of the nonferriferous layers is coarsely crystalline and clear, and the microscope reveals an inconsequential amount of other material. In many of the relatively finer-grained layers, however, the fluorspar is in the matrix, between and surrounding rhombs and grains of ferriferous carbonate (see pls. 10, *B*, 12). From this mode of occurrence it is inferred that the alternation of coarsely crystalline pure fluorspar with impure layers of much finer texture reflects differences of composition and texture in the orginal layers of the rock.

Schwerin [20] has ascribed the crystal-lined cavities and vugs to reduction of volume attending the formation of CaF_2 from $CaCO_3$. The stoichiometrical volume change required by this reaction, however, obviously would form a larger amount of open space than is now apparent; therefore it seems necessary to assume that additional CaF_2 was precipitated from solution. Such a process would explain, also, the lack of structural distortion of the replaced beds.

Two alternative explanations for the formation of the comb structure by replacement are suggested.

According to one hypothesis active fluoriferous solutions from a feeding fissure proceeded along the purer limestone beds, progressively replacing the limestone. Hydrofluoric acid would easily and quickly react with the calcium carbonate of the limestone to form calcium fluoride, according to the reaction:

$$H_2F_2 + CaCO_3 \rightarrow CaF_2 + H_2O + CO_2$$

The ratio between the amount of $CaCO_3$ dissolved and the CaF_2 formed would be completely stoichiometrical, and as the specific volume of CaF_2 is only about two-thirds the specific volume of $CaCO_3$ the fluorspar thus formed by the above reaction would have been of

[20] Schwerin, Martin, An unusual fluorspar deposit: Eng. and Min. Jour., vol. 126, No. 9 (Sept. 1, 1928), pp. 336, 339.

insufficient volume to fill completely the space that was occupied by the replaced calcite. In any solution cavity thus formed, additional fluorspar, existing as CaF_2 in the mineralizing solution and picked up by these solutions because of reactions along the paths of travel, could be precipitated almost immediately, so that at no time would the open space be extensive. This process would result in the building up of crystals from the walls of the progressively forming cavity toward its center. Fundamentally this becomes a comb structure similar to such structures formed, without replacement, in open fissures by simple deposition from solutions. The fluorspar added to that formed by replacement might indeed appear to belong to a second generation, whereas, in reality, it belongs to a single and continuous genetic epoch of mineralization, although, as pointed out by Bastin,[21] an inconsequential amount of fluorspar may be interpreted as having been deposited subsequently to that of the main body.

A second hypothesis for the development of comb structure by replacement along the bedding of the limestone depends upon the relative permeability of the different beds of the limestone. As already remarked, weathered exposures of the limestone display layers of different composition. The siliceous and ferriferous layers appear to have been less readily replaced by CaF_2 than the purer calcite layers, but, in some places at least, they are seen to be more porous, so that such beds might have afforded more opportunity for the entrance and travel of fluoriferous solutions, whether liquid or gaseous. Possibly with these more porous, though impure, layers as more readily permeable channels of access, they became more quickly impregnated with hydrofluoric acid solutions which then attacked and replaced the adjacent denser and more calcitic layers, working into such layers from both sides toward the middle. If this occurred, the "comb" crystals of fluorspar in part represent true metasomes.

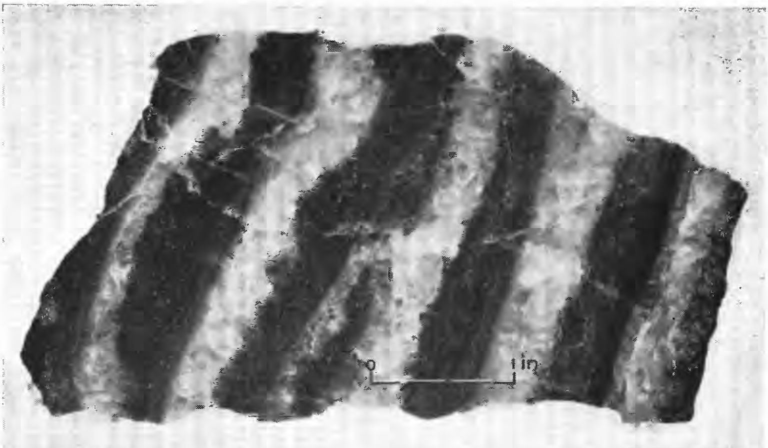
The alternation of layers of fluorspar with layers of quartz crystals, or with layers of silicified limestone, as found at the old Cave in Rock mine and places on Lead Hill, requires a special explanation. Close examination of the "sub-Rosiclare sandstone" reveals that it is made up of two kinds of alternate layers, one kind being dominantly calcitic material and the other being dominantly clastic quartz grains. Both represent sedimentary layers as originally deposited. All of this rock is cross-bedded. Fluoriferous solutions might be expected to develop fluorite in the calcareous beds according to the reaction:

$$(1) \quad H_2F_2+CaCO_3+CaF_2+H_2O+CO_2;$$

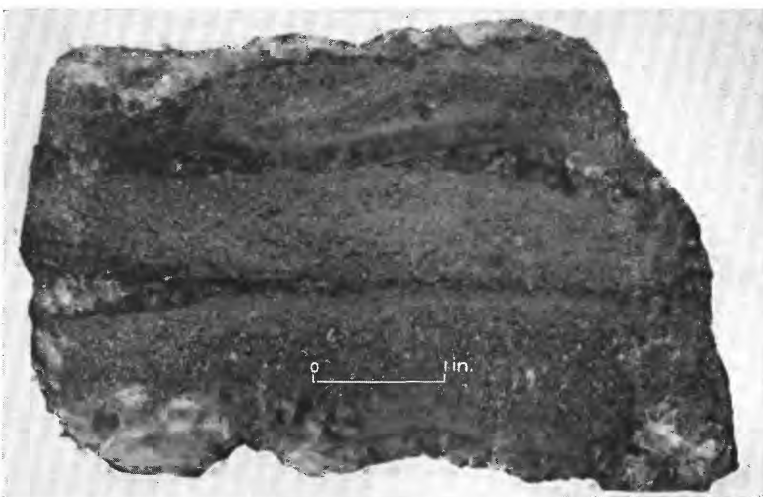
---

21 Bastin, E. S., The fluorspar deposits of Hardin and Pope Counties, Ill.: Illinois Geol. Survey Bull. 58, p. 57, 1931.

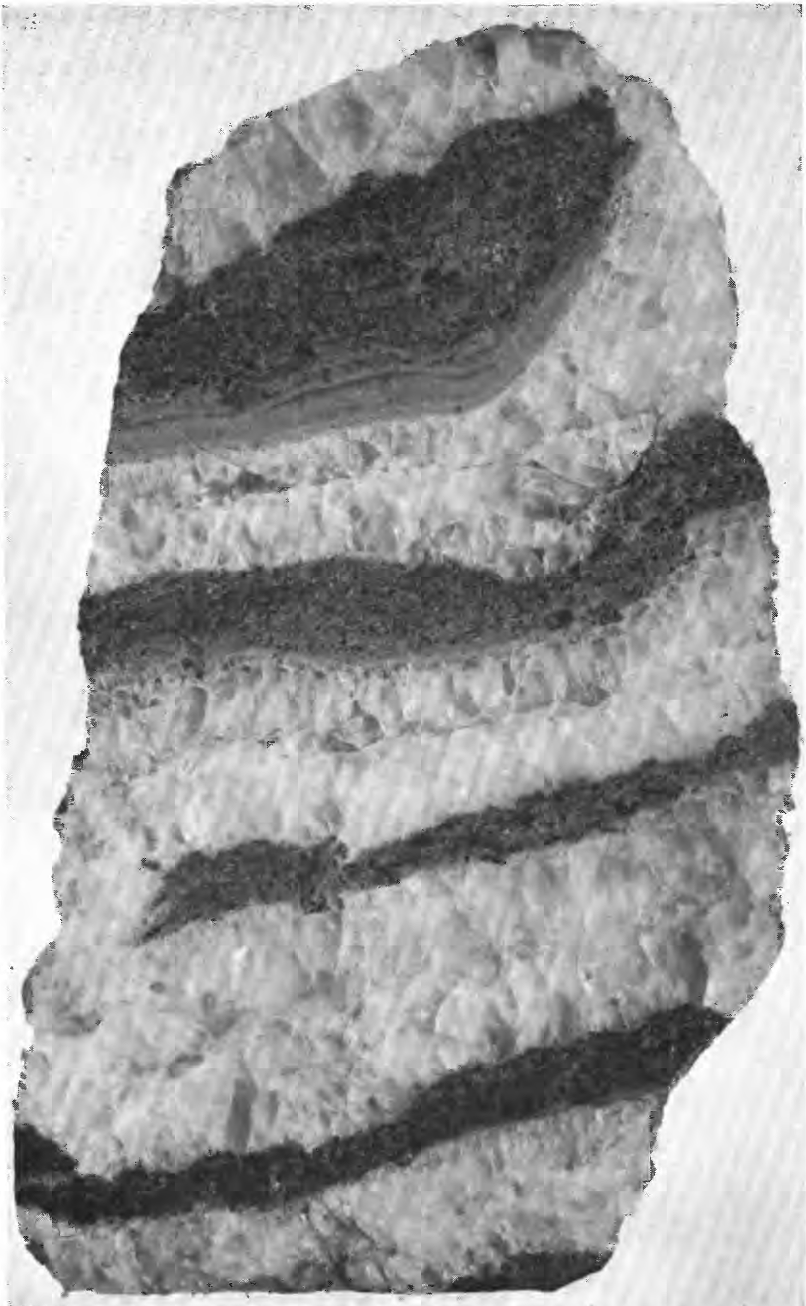
SPECIMEN OF HIGH-GRADE FLUORSPAR ORE FROM SPAR MOUNTAIN SHOWING COMB STRUCTURE AND VUGS.



A. SPECIMEN OF HIGH-GRADE "COON-TAIL" FLUORSPAR FROM SPAR MOUNTAIN.

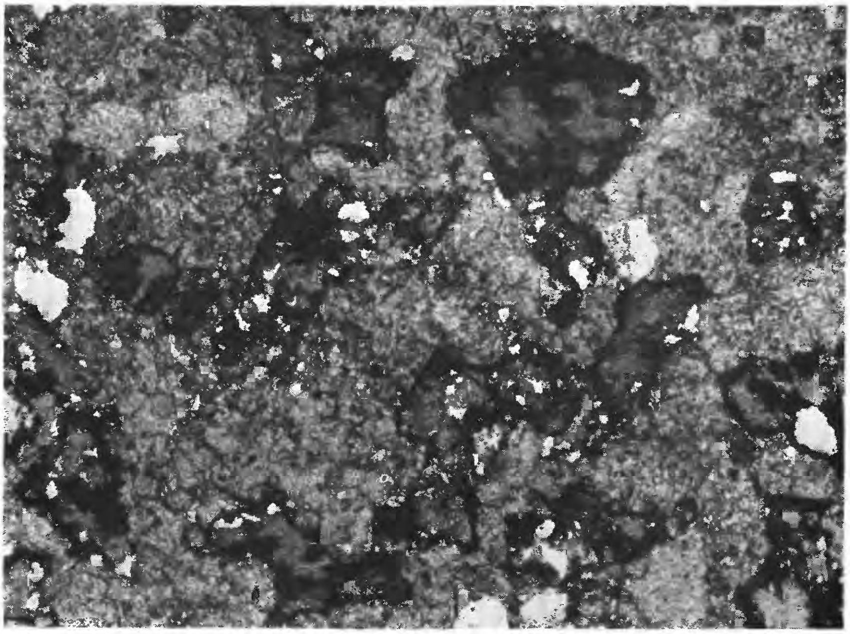


B. SPECIMEN OF LOW-GRADE MATERIAL FROM SPAR MOUNTAIN SHOWING STRATIFICATION.

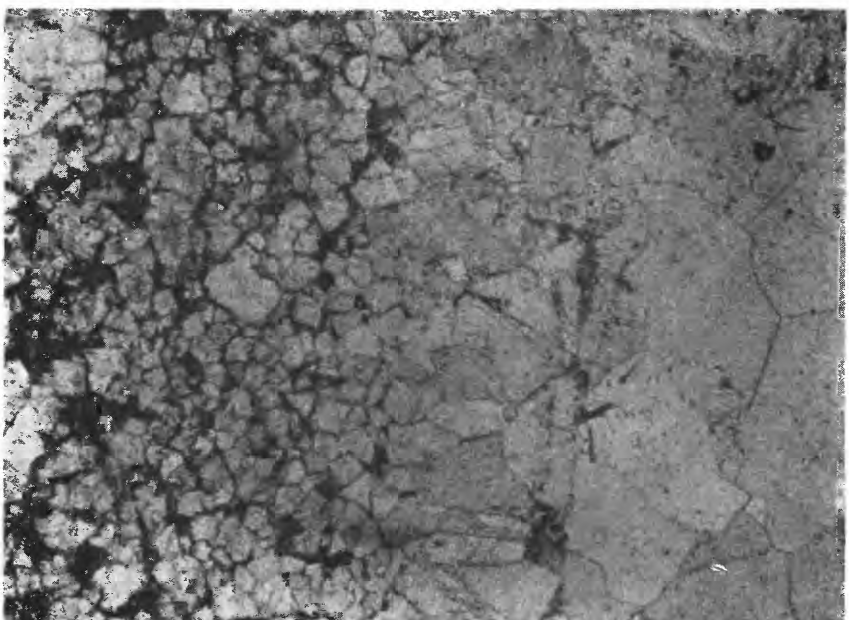


SPECIMEN OF GOOD ORE FROM SPAR MOUNTAIN.

Shows wide colorless bands of pure fluorspar and narrow bands of impure fluorspar that contain unreplaced rhombs of carbonate.



A. PHOTOMICROGRAPH OF AN IMPURE FLUORSPAR BAND SHOWING UNREPLACED FERRUGINOUS CARBONATE GRAINS AND QUARTZ.



B. PHOTOMICROGRAPH SHOWING CONTACT BETWEEN COARSE-TEXTURED AND FINE-TEXTURED BANDS AND INTERSTITIAL IMPURITIES.

in the siliceous beds, on the other hand, the following reactions might prevail:

$$(2)\quad 2H_2F_2+SiO_2 \rightarrow SiF_4+2H_2O,$$
$$(3)\quad SiF_4+2CaCO_3 \rightarrow 2CaF_2+SiO_2+2CO_2.$$

Thus the silica of the original sand grains might first be dissolved by hydrofluoric acid and then reprecipitated, under the influence of an excess of $CaCO_3$, as quartz crystals. A similar origin may be ascribed to the druses of minute quartz crystals in the fluorite layers. In similar fashion there might well result a silicification of the calcareous layers by a matted aggregate of minute "feathery" quartz crystals, as described on page 33. Plate 9 illustrates such layers of quartz crystals alternating with layers of fluorite.

In Schwerin's paper is a quotation from a private report by C. W. Greenland attributing reorganization of the silica to the action of fluoriferous solutions. This change could have been effected by the reactions given in equations 2 and 3 above. These reactions, however, indicate that the deposition of the fluorspar and of the quartz were at least in part contemporaneous, and not separated by a time interval as suggested by Greenland.

QUARTZ

The modes of occurrence of quartz are described on page 32, but the paragenetic relations call for some further comment. That some of the quartz was deposited subsequently to the fluorspar is indicated by the druses of quartz crystals deposited upon fluorspar in some of the layers, vugs, and larger cavities. Microscopic replacement crystals of quartz also occur in the less pure, fine-grained layers of some of the ore bodies, though rarely in sufficient amount to be detrimental except, perhaps, in border zones. The writer has observed no evidence, however, that all the quartz was deposited later than the fluorspar; it appears, rather, that the two minerals were in part contemporaneous, but that deposition of quartz continued after that of the fluorspar. This overlapping of the minerals in paragenetic sequence is in accord with the time relations noted for the vein deposits of the entire Illinois-Kentucky field, as described in earlier reports.[22]

SULFIDES

The deposition of the sulfide minerals galena, sphalerite, chalcopyrite and marcasite appears to have begun during the later stages of fluorite deposition and to have continued beyond it. This is also in accord

[22] Currier, L. W., Fluorspar, lead, and zinc, in Weller, Stuart, and others, the geology of Hardin County Ill.: Illinois Geol. Survey Bull. 41, 1920. Currier, L. W., Fluorspar deposits of Kentucky: Kentucky Geol. Survey ser. 6, vol. 13, p. 59, 1923. Bastin, E. S., The fluorspar deposits of Hardin and Pope Counties, Ill.: Illinois Geol. Survey Bull. 58, p. 26, 1931.

with the sequence of mineralization found in the vein deposits.[23] The formation of marcasite rather than pyrite was probably due to the high acidity and epithermal character of the depositing solutions.

STRATIGRAPHIC RELATIONS

Fluorspar deposits have been found at several stratigraphic horizons in the mapped area, most of them within the upper part of the Fredonia member of the Ste. Genevieve limestone. The thickest, richest, and most extensive fluorspar bodies so far discovered are found in the Fredonia limestone member immediately below its contact with the Rosiclare sandstone member, whose basal shale bed constitutes the roof of the fluorspar bodies in the principal mines. It has become axiomatic in the field that the most important fluorspar deposits are to be sought at this horizon. According to the theory of origin outlined on pages 47–51, however, bedding-replacement deposits might be found at other horizons in the limestones, depending upon whether or not the lithologic sequences and structures at such horizons were favorable.

At several places in the district minor bedding-replacement deposits have, in fact, been found below dense limestone beds, silicified limestone beds, and compact sandstone or quartzite beds, all within about 60 feet below the base of the Rosiclare sandstone. At no locality yet discovered, however, is there evidence that the conditions at these horizons were as favorable for localization of deposits as beneath the basal shale of the Rosiclare sandstone; these lower deposits are apparently smaller, thinner, and less continuous than those of the main ore-bearing horizon. Other than the Rosiclare sandstone, the unit known locally as the "sub-Rosiclare sandstone" has thus far shown most promise. The old Cave in Rock mine is at this horizon, and recently the Benzon Fluorspar Co. has found fluorspar deposits at the same horizon in the lowlands east of the escarpment. These deposits have not yet been opened to an appreciable extent; consequently their probable economic importance cannot be judged at this time.

As already mentioned, a small bedding-replacement deposit beneath a dense limestone bed near the base of the Fredonia limestone occurs three-fourths of a mile northeast of the village of Cave in Rock. A prospect called the Miller mine was opened here in 1917 but was soon abandoned.

Although, as just pointed out, bedding-replacement deposits may exist at many horizons in the Ste. Genevieve limestone, and even in limestones below it, the minor structures that seem to have controlled the deposition of bedding-replacement deposits would not be determinable at the surface over deep-lying deposits, which would thus be discoverable only by costly drilling.

[23] See references given in footnote 22.

STRUCTURE OF THE DEPOSITS

GENERAL FORM OF THE ORE BODIES

The ore bodies are roughly tabular elongated masses tending to lenticular shapes, and generally lie with the long axes parallel to local joints and fold axes. The limits of individual ore bodies are economic rather than sharply defined, in many places, and a single fluorspar deposit generally shows considerable variation in thickness. Variations in thickness and forms are illustrated by plate 5, which was drawn from data obtained underground in four mines of the district. The method of studying these features consisted in constructing a contour map of the roof of the ore bodies—that is, the base of the Rosiclare sandstone member—and measuring the thickness of the mineralized zone at many places.

RELATION OF ORE BODIES TO MINOR FOLDS

The contours shown in plate 5 indicate the shape of the roof of the mineralized zone in the mines that were accessible for study. Variations in altitude of the shale bed appear to be due to structural deformation rather than to deposition upon an old erosion surface, because the bedding laminae of the shale are parallel to the plotted surface. The troughs and rises indicated by the contours have definite trends for the most part, their axes being parallel to other principal deformational features of the region, chiefly the joint systems and faults. An interpretation of the structure of the same horizon for the entire developed area and for some additional ground is presented in plate 4. The data for this structural map was obtained partly from actual exposures of the Rosiclare sandstone along the escarpment, partly from records of scattered drill holes in areas adjacent to the mines, and partly from the mine maps upon which plate 5 was based. Therefore, the contours shown in plate 4 are necessarily generalized, because they were compiled from three sets of data of different degrees of accuracy.

It is evident from plate 5 that most of the thickest mineral bodies are elongated parallel, or nearly so, to the axes of the folds. The heaviest mineralization has occurred, apparently, on the narrow, sharp, pitching folds although it is not entirely confined to such positions. Most of the richer ore bodies seem to be on the flanks of folds, and nearer the synclinal troughs than the anticlinal crests. Mine development, therefore, should generally follow down the pitch of the roof to reach richer areas, if drifting has been carried along a structural "high," or anticlinal crest. In two places thick ore bodies occupy the crests of anticlines but both of these folds are particularly sharp. In general, broad crests or troughs, as indicated by wide spacing of contours, are apt to be more thinly mineralized than areas of sharper folding. These relations of ore bodies to roof contours are clearly seen in many places underground where development has been carried down the dip of the roof, notably in part of the Crystal mine (see pls. 5, 13, *A*).

Although this correlation of ore deposits with small local folds may be of considerable importance to operators during the development of a mine, it will probably be of little service in prospecting or exploration, because its applicability in such operations depends upon the acquirement of a considerable amount of accurate data from many closely spaced drill holes, and the expense of getting enough of this information to be serviceable would generally be too great. Lack of rock exposures renders surface data entirely inadquate for determining the positions of such minor structures.

ROOF VEINS

Veins of fluorspar cut the roof rock in many places in the mines. All these veins are very narrow, generally less than an inch wide, but they are impressively persistent, and some of them may be followed continuously for long distances in the workings. For the most part they belong to two sets, one having a course N. 45° to 60° E., the other and less common set trending N. 60° to 80° W. The approximate coincidence of their trends with the regional axes of major and minor deformation leads to the belief that the fissures in which these veins were deposited were genetically connected with the faulting and folding of the country rock and that, in large part, they represent tension joints in the places of sharpest bending and twisting of the strata.

Inasmuch as these veins are closely associated with and intersect the ore bodies in some places, it is customary in some of the mines to follow them during development as "leaders" to ore bodies. The roof veins are not, however, necessarily above the thickest parts of the bedding-replacement bodies, but in many places they occupy lateral positions along the folds. Some of them even cross the folds at approximately right angles, but, though the fissures that these veins fill were probably also tension cracks and were formed contemporaneously with the longitudinal roof fissures, they differed from the longitudinal fissures somewhat in mode of origin. Roof fissures of both types seem to mark sites of deformation rather than intense mineralization; they probably never acted as the main channels of access for mineralizing solutions, hence their lack of close and consistent association with major ore bodies.

At the Crystal mine several roof fissures were followed parallel to the long axis of the ore body (see pl. 14). In this mine the ore body is situated on the limb of a pitching syncline, of northeast trend, along which the prominent roof fissure veins are spaced rather evenly, though the spacing is somewhat closer where dips are steeper. Plate 13, *A*, shows the pitch of the roof and the related variation in thickness of the ore body at one place in drift No. 3.

At a face in the No. 1 adit of the Pittsburgh Fluorspar Products Co., on the east side and near the top of Lead Hill, two diverging ore bodies were found to follow distinct sags in the roof. Several veinlets in the roof follow the centers of the sags, and it was below these that ore bodies were thickest.

In the Lead adit of the Benzon Fluorspar Co., a similar relation of thick mineral zone to roof sags and veinlets was seen at two points. It was reported that roof seams in this mine were the best guides in development.

In a pillar near the shaft in the mine of the Crystal Fluorspar Co., two narrow roof veins were observed above wide veins that extended along a fault fissure of a few inches displacement in the limestone below the roof. Here the fluorspar body spreads out appreciably just below the cap rock, and the vein continues downward in the floor.

FLOOR VEINS

At several places veins were found in the ore horizon filling fissures that probably served as channels of access through which the mineralizing solutions rose. These veins appear in the floors of drifts and extend upward toward the roof, widening rather abruptly upward, and passing laterally into the characteristic horizontally layered mineral bodies, in cross section the structure roughly simulating a mushroom (see fig. 5). The structure was noted in 1917 at the old Miller mine on the west side of Lead Hill.[24] Here a thin bedding-replacement deposit was seen to continue downward into the floor as a vein. At the No. 5 adit of the Pittsburgh Fluorspar Products Co., in the south end of Lead Hill, about 40 feet below the Rosiclare sandstone, a dense limestone bed forms a cap rock for a thin bedding-replacement deposit of the usual type. At the drift face a vein of coarsely crystalline fluorspar extended downward into the floor, directly beneath a slight sag in the floor rock. At the floor level the vein was narrower, having pinched to about a foot wide, and had been followed for some distance along the floor. In the roof directly above the vein at the face a 3-inch roof vein was seen. This "center seam" had been followed in drifting from the outcrop.

BOUNDARIES OF MINERAL BODIES

The contacts of the bedding-replacement bodies with the roof rocks are sharply defined. In some places a relatively thick layer of pure, transparent fluorspar is found at the contact, suggesting that the upper layers of the replaced limestone beds at these points were particularly pure. In most places, however, the topmost layers of fluorspar are thin. They commonly follow the roof contact without deviation, but inclined layers just beneath—believed to represent cross bedding in the original limestone—terminated against or

[24] Currier, L. W., op. cit. (Ill. Geol. Survey Bull. 41), p. 255.

coalesce with the top layers. This feature is represented in plate 8. Bedding veins of clear, crystalline fluorspar are found in places in the roof shale above the contact, but these are doubtless fissure fillings rather than replacement bodies; an explanation for the origin of these flat veins is given below.

At the contact also may be found thin, lenticular cavities, that rarely exceed 3 or 4 feet in maximum dimension. They are commonly lined with crystals of fluorspar, some of which are as much as 6 inches in diameter. It would appear that local solution greatly exceeded deposition at these places during the process of replacement. Such cavities, however, may have resulted only in part from the

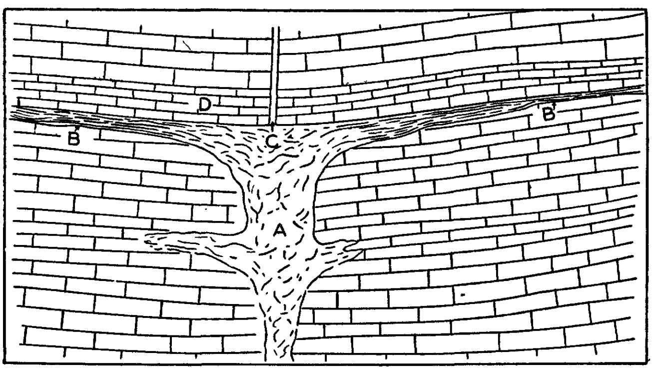


FIGURE 5.—Diagram illustrating "mushroom structure" as observed in adit No. 5 of Pittsburgh Fluorspar Products Co. and at abandoned workings of Basic Mineral Co., Lead Hill. A, Coarse vein fluorspar; B, banded fluorspar; C, roof vein; D, dense cap rock.

reduction in volume that has been attributed to the difference in specific volumes of fluorspar and calcite as pointed out by Schwerin[25] and elaborated upon in this report; to some degree the cavities may also represent local slumping or settling into solution cavities in the limestone below.

Laterally the bedding-replacement layers converge and coalesce, and ultimately pinch out in the limestone. In many places a massive, compact limestone floor of very dense texture limits the mineral bodies at the base in places and also the surface of the limestone rises toward the roof along the upper side of the ore body serving to reduce and pinch out the replaced horizon (see pl. 13).

PARTINGS

Within the mineral bodies, unmineralized beds from a fraction of an inch to several feet in thickness are often encountered. Some of these layers are thin shale beds, and some are limestone beds that,

[25] Schwerin, Martin, an unusual fluorspar deposit: Eng. and Min. Jour., vol. 126, No. 9 (Sept. 1, 1928), p. 309.

being more argillaceous or very dense textured, were not readily replaced. At an adit portal of the Green mine a layer of dense-textured ferriferous limestone about 2 inches thick was seen as a parting between beds of banded fluorspar. At several places in the Victory mine beds of dense or partly crystalline brown limestone, of variable thickness, occur as partings between beds of typical "coon-tail" fluorspar. Plate 15, *A*, illustrates a similar limestone bed, partly fractured and slightly mineralized by veinlets and streaks of fluorspar.

BEDDING VEINS IN ROOF SHALE

At many places in the several mines flat-lying thin veins of coarsely crystalline fluorspar without comb structure occur in the shale roof adjacent to thick mineral bodies (see pl. 15, *B*). Such veins bifurcate and coalesce, but for the greater part follow the stratification planes of the shale. It is believed that these veins were formed by deposition in more or less open spaces between shale layers, rather than by progressive replacement, as the boundaries are sharp and enclose no fragments of shale that appear to be replacement remnants.

In the Crystal mine, at a point near the adit portal, a mixture of coarsely crystalline fluorspar and shale fragments is exposed at the roof of the fluorspar body. The promiscuous arrangement of the shale fragments in the fluorspar and the steep pitch of the roof at this place indicate dynamic deformation with attendant fracturing of the roof material, probably at the beginning of the epoch of mineralization.

Two processes probably operated in producing the phenomena just described. Progressive replacement of limestone by fluorspar, as outlined in previous pages and for the reasons stated therein, resulted in a net volume reduction. In part this reduction was probably offset by deposition of CaF_2, existing as such in the solution and migrating from other points; in part, however, the net result was the progressive development of open spaces in the limestone horizon just below the roof. During the temporary existence of such spaces, the collapse and spreading apart of overlying shale beds progressively afforded interbedding space for direct precipitation of fluorspar. As open space existed temporarily at these points and below the shale, the crystallization of the fluorspar between shale laminae assisted in spreading the layers farther apart, until the voids were entirely filled or the supply of solutions failed. In places some spalling of shale fragments into local cavities may well have taken place during the time of mineral deposition.

Open spaces in the shale roof may have been brought about by some spreading of the layers on the steeper parts of the folds by the slippage and displacement of the beds as a result of the folding. Such a process would tend to weaken the shale along bedding planes, and to breciate the layers without much rotation of the fragments. Open spaces may also have been produced by the actual spreading apart of more competent layers above and below the thin stratum of shale at the base of the Rosiclare sandstone.

FLUORSPAR CONTENT OF MINERAL BODIES

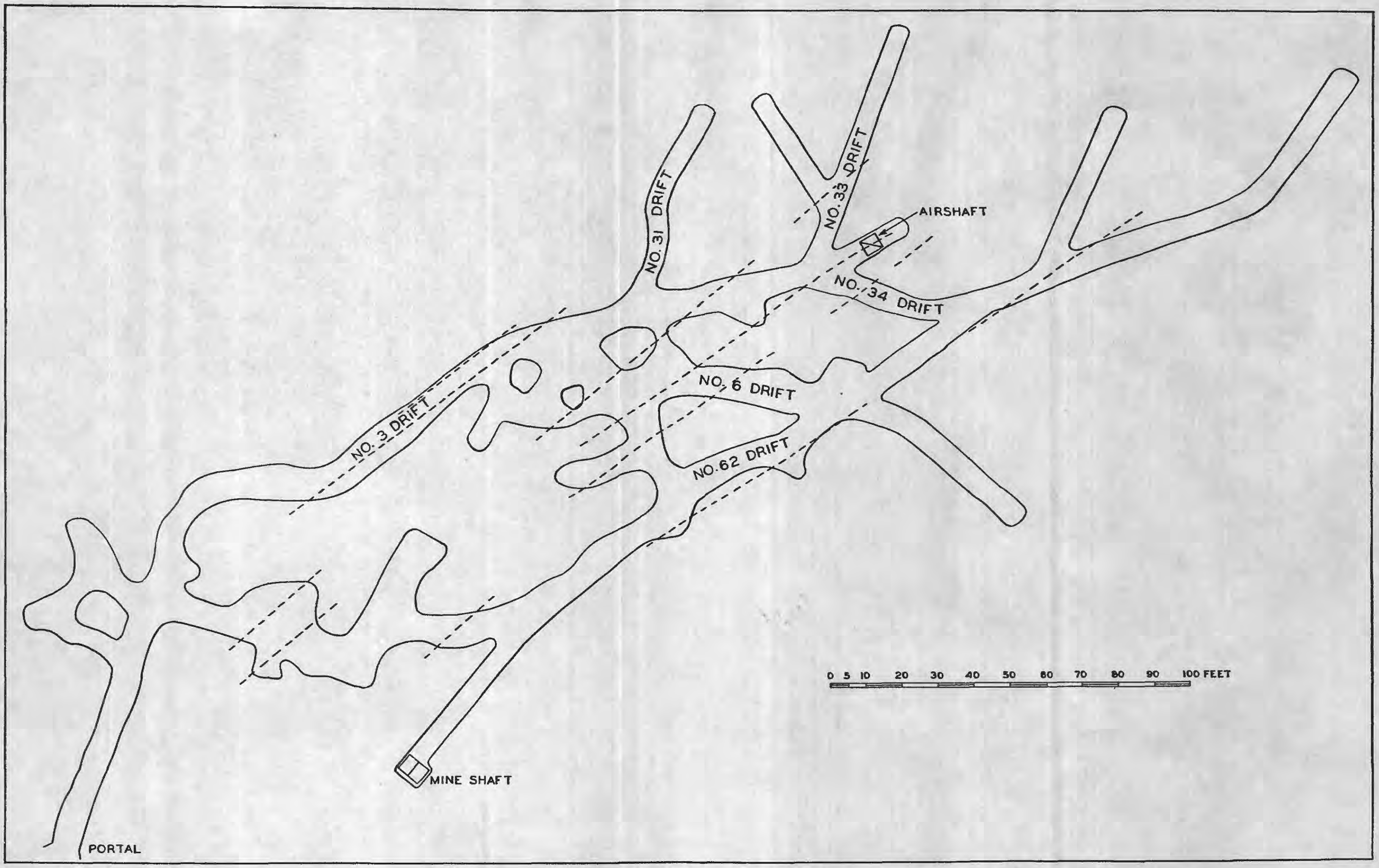
From the structural and textural characteristics of fluorspar deposits as described on foregoing pages it is clear that the calcium fluoride content of mined material must vary widely. The variations in thickness of the layered ores, the presence of partings, the gradual merging of border zones into unmineralized limestone, the differing relative thicknesses of pure layers and impure layers and probably several other factors would all tend to the same result. Information given by the several operators indicates that, according to mining practice, mill heads average from 50 percent to 80 percent calcium fluoride. That the minimum of this range is so low is due to the fact that some of the deposits have disintegrated at the surface and have become mixed with residual soil. Such deposits are mined by steam shovel and the crude ore is sent to the mill for washing and concentration. Their silica is mostly in the form of admixed clay and sand, which are readily washed out in the first stages of milling. In material from underground workings the average CaF_2 content appears to be about 70 percent, but the maximum is much higher than that of the surficial ore bodies and the average SiO_2 content is accordingly much lower. Because of the exceptionally high grade of some parts of the solid ore bodies it has been possible to mine exceptionally low grade material from the border zones or from thinner and poorer ore bodies, so that by mixing the two, mill heads would be obtained that would yield a product of standard metallurgical grade—that is, containing 85 per cent of CaF_2 and 5 per cent (or less) of SiO_2. Indeed, parts of some ore bodies have yielded ore that contained 90 per cent or more of CaF_2 and less than 5 per cent of SiO_2. Selective mining and marketing of high-grade ore has not been encouraged by market prices for the higher grades of fluorspar, because by mixing the ores it has been possible to prolong the life of the mine, to conserve the resources, and to obtain a greater financial return in the long run.

The differences in fluorspar content between the two kinds of alternating layers of the typical bedding-replacement ores are not great, and are, indeed, far less than might be expected from the contrasting appearances of the layers. The finer-grained, less pure layers probably contain, for the most part, from 70 to 85 per cent of CaF_2, except in the leaner, marginal parts of ore bodies, and one analysis of the "sandy-looking" layers was reported to show 95.09 per cent of CaF_2, 4.12 per cent of SiO_2, and 0.86 per cent of $CaCO_3$.[26] It is therefore not necessary to separate the layers in milling.

[26] A. H. Cronk, personal communication.

A. VIEW IN DRIFT 3, CRYSTAL MINE.

B. EXPOSURE OF FLUORSPAR HORIZON AT PORTAL OF LEAD ADIT, BENZON FLUORSPAR CO.



DRIFT MAP OF CRYSTAL MINE.

Position of roof fissures indicated by broken lines. Courtesy of Crystal Fluorspar Co.

A. FACE OF A ROOM IN CRYSTAL MINE.

B. BEDDING VEINS IN ROOF SHALE, VICTORY NO. 1 MINE.

ORIGIN AND GEOLOGIC HISTORY OF THE DEPOSITS

In origin and geologic history, the bedding-replacement deposits of the Cave in Rock district are, in their general aspects, similar to the vein deposits that characterize the rest of the Illinois-Kentucky field. The source and character of fluoriferous solutions and the time of deposition are believed to be the same for both types of deposits. Only in regard to the details of structural control does the genetic history of the bedding-replacement deposits differ from that of the veins. Theories of origin for the entire field have been stated in previous publications, already cited. A brief summary is presented here, however, so that the genetic relations that the writer believes to exist between the bedding-replacement deposits and the veins may be clearly understood.

Three general factors are foremost in any problem relating to the origin of mineral deposits formed by circulating underground waters. These are (1) the source of the solutions; (2) the channels of access from the points of origin of the solutions to the sites of mineral deposition; and (3) the conditions that determined the sites of deposition of the mineral bodies. As regards the sites of deposition, the problem also involves the geologic processes by which the host rock was prepared for mineral reception.

The source of mineralizing solutions for the entire fluorspar field is believed to have been a deep-lying mass of molten rock material, or magma, that existed at considerable depth, doubtless several thousands of feet below the present surface.

The geologic structure of the Illinois-Kentucky fluorspar field has been described as a large oval dome that collapsed to form a mosaic of fault blocks and wedges. The doming of the strata may have been caused by the upward pressure of a large body of magma intruded at considerable depth, or it may have been caused by crustal forces that warped and uplifted the strata and thus permitted magma to invade the space, nearer the surface, in which pressure had thus been diminished by displacement of the strata. The presence of an underlying magma body that was intruded by either of these processes is indicated by the widespread occurrence of dikes in the domed area, most of the exposures of which are found in the broad central part of the field. As these dikes are generally not found in fault fissures, and some of them are offset by major faults, they must have been intruded before the dome collapsed. The striking symmetry of the Hicks dome, in the northwestern part of the field, suggests that the dome was caused by intrusion of a laccolith—an igneous body shaped like a mushroom, and forced between layers of stratified rocks—but this local intrusion could not have caused the doming of the field as a whole.

The general fault pattern of the field is believed to be more suggestive of regional warping by crustal forces than of deformation by simple uplift directly due to igneous intrusion. The main faults appear to be grouped roughly into three broad belts transverse to the long diameter of the field. In general, the trend of these belts is northeasterly, but from northwest to southeast the trends of the faults become progressively more easterly, and in the extreme southeastern part of the field the faults trend practically east-west. According to the geologic map of Kentucky narrow faulted belts extend from the fluorspar field for relatively long distances into the central and eastern parts of the State.

Bucher,[27] indeed, has suggested that an incipient arcuate geosyncline follows the west side of the Mississippi embayment, and that its axis runs generally parallel with the Mississippi Valley as far north as southern Illinois, whence it swings to the northeast, following the Ohio River Valley in a general way and conforming broadly in trend with the Appalachian geosyncline. It is interesting to note, in this connection, that the sharp bend of the axis of this postulated geosynclinal furrow lies within the broadly domed fluorspar field.

It seems likely, therefore, that the region was broadly warped and domed by widespread crustal forces, that invasion by magma accompanied or followed this deformation, and that the igneous activity was followed by collapse and settling of the uplifted and warped area, giving rise to the major faults after solidification of the igneous material. The Cretaceous beds of western Kentucky apparently were faulted, so that a part, at least, of the faulting must have been of post-Cretaceous age.

Late hydrothermal emanations from the deeper part of the magma basin ascended along major fault fissures, which must have cut through the congealed upper part of the deep-seated magma as well as through the overlying strata. These emanations were especially rich in fluorine, so that hydrofluoric acid, formed by hydrolysis, was relatively abundant in the ascending solutions. Wherever calcium carbonate (as limestone or as vein calcite) was encountered along the paths of circulation, chemical reactions resulted in the formation of fluorspar. So long as the upward flow of the solutions was relatively unimpeded, by virtue of the more or less open character of the fissures, a considerable excess of hydrofluoric acid probably remained in the solutions and was carried upward until it gradually became used up by reaction with calcium carbonate encountered along the fissures. It is a natural result of such action that some of the fault fissures contain fluorspar through a large vertical range. For long distances and in many places along faults, also, smooth, compact, slickensided walls gave little chance for replacement of the wall rock, even where it was composed

[27] Bucher, W. H., The deformation of the earth's crust, pp. 354-357, Princeton Univ. Press, 1933.

of limestone, except at intersections with other fissures. But even where wall rocks could not be replaced vein fluorspar was probably deposited directly from solution wherever the progressively decreasing pressure and temperature of the solution made it unable to carry the calcium fluoride obtained at lower horizons. Wherever crystalline calcite was encountered as fissure filling, as, for example, between walls of the thick Ste. Genevieve limestone and lower formations, fluorspar was deposited both by reaction of the hydrofluoric acid of the solutions with calcite, and through volume-for-volume replacement of calcite by the calcium fluoride carried in the solutions.

The formation of the characteristic bedding-replacement deposits of the Cave in Rock district seems to have been due to a combination of certain structural and stratigraphic conditions peculiar to that district. The forms of the principal deposits and their relation to the shale at the base of the Rosiclare sandstone member have led to the belief that this lithologic unit effectively shut off or at least impeded the rise of solutions along minor fissures, retarding their flow and causing them to spread laterally along the shale. Other dense beds below the shale, and probably some above, acted similarly, but apparently to a lesser degree. Reactions of the solutions with the more penetrable limestone beds directly below comparatively dense cap rocks thus developed replacement bodies, which preserved the bedding and cross-bedding laminae of the replaced limestone.

The channels of access for these solutions were prominent joint fissures and minor fault fissures, connected with larger fissures, which in turn were connected ultimately with a major fault zone, probably the Peters Creek zone. The writer's conception of the entire aggregation of the feeding fissures is that of more or less diverging sets, along the uppermost and outermost members of which there was little or no displacement, in marked contrast with the fissures in which veins were deposited elsewhere in the fluorspar field. The minor fissures of the Cave in Rock district, according to this theory, either extend upward just to the cap rock, or, in passing through the basal shale of the Rosiclare sandstone (or other comparatively "tight" horizon), are sharply narrowed, owing to the incompetency of the shale to develop or preserve extensive and relatively wide fissures. In the shale such cracks would tend to be closed by flowage and folding as well as by slippage along the weakly coherent beds, whereas in the relatively competent limestone beds fissures could remain partly open, the walls being supported in places, of course, by points of contact along the fracture.

Such a system of minor fissures, dying out upward at horizons of favorable differences in lithologic competency, might well be more numerous in the marginal part of a domed area than in the more central part, where faulting is prominent. In the marginal belt the regional strain features become progressively weaker toward the border and finally disappear. Thus a combination of geographic position with stratigraphy, structure, and the proximity of a major fault zone made the Cave in Rock district peculiarly favorable to the formation of bedding-replacement deposits. Probably some other marginal areas of the Illinois-Kentucky field possess a similar combination of favorable features, and may ultimately yield similar deposits. The detection of such areas is certain to be difficult, in general, because of the lack of pronounced displacements of the strata, the general obscurity of minor folds and faults that appear to be necessarily associated with such deposits, and the fact that the depos-

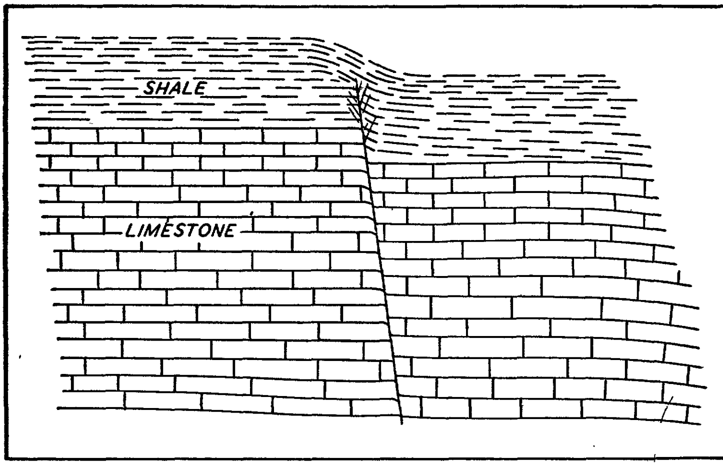


FIGURE 6.—Diagram illustrating formation of a flexure in flexible beds over a minor fault in brittle beds.

its themselves are parallel to the bedding of the strata and hence would be less commonly exposed at the surface than would veins.

The sites of deposition were thus near the minor terminal fissures of a complex system, developed during the doming and faulting of the Illinois-Kentucky field. Minor folding of the strata assisted in preparing the ground for mineralization, by the forming of local minor tension fissures along positions of greatest curvature or steepest pitch, both along the limbs of minor folds and in directions across the folds. In one or two places, as illustrated by figure 6, there is a suggestion that steep pitches of the roof may follow floor fissures of small displacement, as if these minor faults may be represented in the roof rock by flexures. There is no tangible evidence, however, that the roof flexures were generally formed in this way; indeed, the pronounced narrow pitching anticlines and synclines rather oppose this interpretation in some places, as does also the slight sag in the roof observed in the adit at the south end of Lead Hill (see fig. 5).

Erosion after the deposition of the fluorspar deposits removed a considerable but indeterminate thickness of the cover rocks, exposing the mineral horizon along the sides of Spar Mountain and of Lead Hill. Doubtless the mineralized beds once extended farther to the south and east over part of the adjoining lowland.

VIEWS OF PREVIOUS WRITERS

Bain [28] in 1905 briefly described some bedding deposits in the Cave in Rock district and attributed their origin to replacement of limestone strata along the bedding. He explained the comb structure of the layers as an example of "pseudocrustification," with the central lines of the pure layers representing stylolitic contacts between individual layers of the limestone.

The writer's first study of the fluorspar field, made in 1917, included only a brief examination in the Cave in Rock area. At that time a small cut was being operated at the Cave in Rock mine. The workings at Lead Hill were inactive, but part of the Miller mine (Basic Mineral Co.) on the west side of the hill was accessible. The general form and lithologic relations of the deposits were recognized, the "mushroom structure" as described on page 43 was reported,[29] and the relation of the fluorspar to minor fissures was suggested, but it was not possible to determine the structural and textural details as outlined in this report.

Bastin[30] studied the district in 1926. He agrees with the theory of metasomatic origin of the deposits, and also attributes them to mineralizing solutions that followed small fractures and penetrated limestone beds, particularly at the contact between the basal shale of the Rosiclare sandstone member and the underlying Fredonia limestone. He considers that the banding of the deposits is "nearly parallel to the bedding planes of the inclosing rock."[31] He believes, however, that the fluorspar layers do not follow stratification planes exactly, but make various angles with them, that these divergences "demonstrate that the banding is not an inheritance from either bedding or cross bedding of the sediments," and that one of the outstanding features of the deposits is "the common development of a peculiar type of banded ore which implies rhythmic deposition by replacement." [31] Thus, according to him, the bands or layers were formed by diffusion through the limestone bed, outward from cross-cutting fissures and downward from the shale-limestone contact.

Evidence presented through the present report is believed to show that the layers of the Cave in Rock ores represent original stratifica-

---

[28] Bain, H. F., Fluorspar deposits of southern Illinois: U. S. Geol. Survey Bull. 255, pp. 54-58, 1905.

[29] Currier, L. W., in Weller, Stuart, and others, The geology of Hardin County, Ill.: Illinois Geol. Survey Bull. 41, pp. 254-255, 1920.

[30] Bastin, E. S., The fluorspar deposits of Hardin and Pope counties, Ill.: Illinois Geol. Survey Bull. 58, 1931; 16th Internat. Geol. Cong. Guidebook 2, pp. 39-42, 1933.

[31] Op. cit. (Guidebook 2), p. 40.

tion and cross bedding of the replaced limestone, and that the differences in composition between successive layers in the ore deposits reflect differences in texture and purity of original laminae of the limestone. The uniform spacing of the layers through considerable thicknesses, the comb structure displayed by many of the pure layers, the fact that even the less pure finer-textured layers of most of the core consist predominantly of fluorite, and the fact that the layers in some ore bodies consist alternately of nearly pure quartz and fluorspar, all favor the theory of simple bedding replacement rather than rhythmic deposition. Except for this difference in mode of penetration and replacement by fluoriferous solutions, however, both agree that the fluorite bodies were formed by replacement of permeable limestone below dense beds of shale or limestone, and that the sites of deposition were determined by structural features.

POSSIBLE EXTENSION OF THE PRODUCING AREA

The geologic history, mode of origin, and structural relations of the bedding-replacement deposits, as outlined and interpreted in the foregoing pages, suggest that such deposits may be present in places through a considerable area to the northeast of the area of present development. The occurrence of such bodies elsewhere will, of course, be determined by the presence of certain favorable conditions, as outlined above. Bedrock exposures are too sparse and inadequate for complete determination of the potentialities of the unexplored area northeast of the mines, but the formations can be mapped with confidence, and the presence of some minor faults can be inferred from the field data. In addition, the geophysical work done by Mr. Hubbert has indicated definite breaks in the resistivity profiles that can rationally be construed as due to structural disturbances. For these reasons the area to the northeast should be considered worthy of careful prospecting. This can be done satisfactorily only by drilling, for the Rosiclare sandstone is not exposed and, as pointed out in a previous section, it will be found at progressively greater depths toward the northeast. Sinking of prospect shafts would therefore be too costly and it usually is not an economical method of primary exploration. The increase in depth to the favorable horizon will also tend to set economic limits to the development of the deposits. The limits of the geologic map, however, are not related to any known or inferred limits of the area worth prospecting; they merely outline a convenient unit for this investigation.

The formations of the lowland area south and southeast of the escarpment are entirely below the Rosiclare sandstone horizon, which has here been removed by erosion. The "sub-Rosiclare sandstone" appears in a small part of this area. Any bedding deposits present in the lowland must be related to the "sub-Rosiclare" or still lower horizons in the Fredonia limestone. According to the theory of origin outlined above, bedding deposits may be present in places at these lower horizons, providing the structural and lithologic conditions are favorable. The area underlain by the Fredonia limestone is very extensive, but a thick mantle of residual clay conceals details in this rock. It is not possible, therefore, to indicate any particularly favorable ground for exploration in the broad lowlands between the Spar Mountain escarpment and the Ohio River; prospecting by drilling would be entirely of the expensive "wildcatting" variety. Incidentally, much of the low area in question is underlain directly by the St. Louis limestone, a formation in which no certain signs of bedding deposits have yet been found, and which appears to be of more uniform lithologic composition than the formations above.

The long escarpment that extends southeastward from the broad creek valley in the northeast part of the mapped area is favorable prospecting ground so far as the stratigraphy is concerned, for the Rosiclare sandstone is exposed along nearly its entire length; but as geologic investigations made in connection with this report were not carried into that area, no statement can be made regarding its minor structural features. Except at its northwest end, however, this escarpment is remote from any known major or minor fault zone.

Since one of the chief features that characterize the present producing district is its marginal position with respect to the domed area of the fluorspar field, it might be expected that bedding-replacement deposits may be found in other marginal areas of the field. Indeed, at the Renfro prospect, in sec. 23, T. 11 S., R. 8 E., about 5 to 6 miles northwest of Spar Mountain, the dump shows material of the characteristic bedding-replacement type. Here the Rosiclare sandstone and a thin shale bed are present, and there is a mapped fault nearby.[32] The material at this prospect would appear to be significant and to warrant further investigation of the prospect because of the known geologic conditions. The extent to which shale forms the base of the Rosiclare sandstone in this peripheral belt might be one of the vital factors.

Specimens of "banded" fluorspar showing the typical layered structure of the Cave in Rock ores have been obtained also at the dumps of the Hamp mine, 3 miles north of the center of the Hicks dome, where the Rosiclare sandstone is exposed, but no statement can be made regarding the extent of the deposits at this locality. Vein deposits have been worked here intermittently, but so far as could be determined no bedding-replacement deposits of appreciable size have been found during the operations. The following note is repeated from the writer's earlier report:[33]

---

[32] Weller, Stuart, and others, The geology of Hardin County, Ill.: Illinois Geol. Survey Bull. 41, pl. 1, 1920.

[33] Weller, Stuart, and others, op. cit., p. 303.

At a small cut west of the shafts, banded fluorspar of the "bedding" type of deposit was seen. Unlike the fluorspar near Cave in Rock the mineral of these bands was very deeply colored and nearly opaque. When freshly broken, the mineral from this deposit gave a very strong odor of petroleum.

Similar material has been found at the Rose property, and according to Charles Butts,[34] formerly of the United States Geological Survey,

a vein of high-grade fluorspar occurs in the Devonian limestone, and probably in the Hamilton part of it, on Goose Creek, about one mile southeast of Hicks, where it has been prospected and worked on the Rose property. The vein, which lies parallel to the bedding, is apparently a replacement of the limestone layers. The enclosing beds are chert, which also is a replacement of the limestone layers.

Extensive bedding-replacement deposits should hardly be expected to exist in areas of pronounced faulting well within the domed area where vein deposits are common, such as in the Rosiclare district, because the originally more open fissures of major fault zones would not be apt to favor the penetration of minor terminal fissures by large volumes of mineralizing solutions, although some minor replacement along the bedding planes of limestone walls could be expected in places.

SUGGESTIONS FOR PROSPECTING AND EXPLORATION

Bedding-replacement deposits should be sought particularly in marginal areas of minor fissuring, fairly near but not along prominent fault zones, where the Rosiclare sandstone is present and has a shaly base, or where other beds that are similarly compact are underlain by penetrable limestone. So far as indicated by present knowledge of the field the most favorable ground is on the top of Spar Mountain and in the northeastern part of the mapped area and still farther to the northeast. The territory for some distance east of the mapped area seems less encouraging because so far very little fluorspar has been discovered along the escarpment that trends to the southeast; however, the anomalous strikes and dips along the eastern boundary of section 35, as shown on Weller's map [35] indicate structural disturbance in that locality. Those parts of the mapped area in which minor faulting or warping of the beds is indicated by geologic data, or suggested by resistivity anomalies, should be most favored, but other parts, in which faulting or warping is not evident on the surface, should not be omitted, for most of the minor structural features are generally obscured on the surface and hence could not be recognized by ordinary geologic methods.

Prospecting for bedding-replacement deposits must generally be carried on by drilling, as shafts are economical only where the expected deposits lie at very shallow depths and where there is some surface

[34] Unpublished manuscript.

[35] Weller, Stuart, and others, op. cit., pl. 1.

indication of favorable structure. Core drilling is unquestionably the most satisfactory drilling procedure, as the stratigraphy and structural features of mineralized beds can best be detected by this method.

During the development of a mine, structural features should be closely observed and progressively mapped, so that gradual changes in the dip of the beds can be constantly noted. It seems clear that for the most part the axes of developed ore bodies tend to follow the structural trends that are regionally characteristic. In places these trends are indicated not only by the roof fissures and the floor veins but also by the axes of minor folds. It also appears that in many places underground development can go from lean to richer portions by following the pitch of the roof—which is essentially the dip of the beds—from the crests of folds or "rolls." This direction would not necessarily be that of the main axis of the individual mineral body, which would most commonly be expected to trend in the direction of structural axes, such as roof fissures, floor veins, and folds axes, and hence would ordinarily be more or less nearly at right angles to the direction of dip of the beds. In the area represented in plate 5, for example, starting in the lean part of an ore body—perhaps at the top or bottom of a fold—and following the dip of the beds, as shown approximately by the contours, would in most places lead to richer zones. The developed areas shown by plate 5 represent a very small proportion of the district upon which to establish a rule, but data do suggest that a structural pattern of control exists and that close attention should be paid to structural elements during exploration and development to the end that this apparent rule may be substantiated or a more exact one established.

MINES AND PROSPECTS

Mine development in the Cave in Rock district presents a constantly changing picture. Because of the comparatively shallow depth to which the known deposits are confined and because they have, for the most part, been entered through adits, it has been possible to develop them from numerous points of attack and rather quickly to abandon individual openings that have been worked out or that have proved unproductive. It has been customary, when an ore body has been opened, to follow it only so long as it yields profitable material. For these reasons the scenes of activity have been constantly shifting from mine to mine or within a mine, the development of new openings being soon followed by their temporary or permanent abandonment. The writer feels that no particular service would be rendered by describing in detail all the accessible mine workings when it would be impossible to give a similarly detailed account of the inaccessible workings that would be essential to a balanced picture. Therefore, only brief and general descriptions of the present workings will be given, together with still briefer statements concerning the locations and general relationships of former openings. Brief descriptions and historical facts relating to these earlier workings have appeared in earlier publications.[36] The locations of all mines and prospects listed here are indicated on the geologic map, plate 3.

Crystal Fluorspar Co.—The mine operated by the Crystal Fluorspar Co. (post office address, Elizabethtown, Ill.), is the most northeasterly mine of the district. It was opened in 1930 through an inclined adit at the base of the eastern slope of Spar Mountain. The underground workings comprise two main drifts, 40 to 70 feet apart, that extend in a general N. 35° or 40° E. direction, and are connected by several crosscuts. Several short drifts also penetrate for short distances into the bordering areas in the northwest and southeast, and small irregular rooms or galleries are developed in the area between the main drifts. The length of the developed area (see drift map, pl. 14), in the summer of 1934 was about 400 feet, and the average width was about 60 feet, but since that time the southeastern drift has been considerably extended to the northeast. A shallow service shaft connects the southwest end of this drift with the surface. A prospect shaft, the Lackey shaft, has been sunk at a point about 550 feet N. 70° E. from the adit portal.

Notable general features seen in the Crystal mine are the steep southeasterly and easterly dips of the shale roof along the northwest (drift 3), the marked thickening of the ore body, from zero at places in the northwest wall, to more than 8 feet down the pitch of the roof (see pls. 5, 13, *A*), and the numerous mineralized roof seams, or "leaders," trending N. 55° to 60° E., parallel to the long axis of the ore body. Along the southeast drift, the roof rises appreciably, but its slope is less than that of the northwest drift, so that the thickest parts of the ore body appear to lie in the center and northwest limb of the synclinal trough.

At a point in the southwest crosscut about midway between the main drifts, a roof fissure showing no appreciable displacement is exposed above a sharp drop in the floor of the crosscut on the south side, in which the exposed thickness of the mineral body is 9 feet; it was reported that fluorspar was followed 5 feet deeper on this side. No floor vein was seen here, but the floor was not carried to the bottom of the mineral zone. There is some suggestion that a displacement of the floor is reflected in the marked warping of the roof and development of a tension crack. In a pillar near the shaft, there appears to be a fault of very small displacement, filled with coarsely crystalline

[36] Bain, H. F., The fluorspar deposits of southern Illinois: U. S. Geol. Survey Bull. 255, 1905. Currier, L. W., Economic geology, in Weller, Stuart, and others, The geology of Hardin County Ill.: Illinois Geol. Survey Bull. 41, pt. 5, 1920. Bastin, E. S., The fluorspar deposits of Hardin and Pope Counties, Ill.: Illinois Geol. Survey Bull. 58, 1931.

vein fluorspar, leading to a narrow mineralized roof fissure. Shale fragments, oriented as if by drag and separated by streaks of fluorspar, were seen in the pillar. Some postmineralization faulting appears to have cut the ore body on the east side of the southeast drift (drift 62).

At a few places, coarsely crystalline calcite appeared in the limestone at the contact with fluorspar, and replacement of the calcite by purple fluorspar was noted.

Benzon Fluorspar Co.—The property of the Benzon Fluorspar Co. covers an extensive area along the east and south slopes of the Spar Mountain escarpment and in the adjoining lowland. The northeastern limit of the property is about a quarter of a mile southwest of the Crystal mine. The property extends southwesterly and westerly, nearly to the Cave in Rock mine. From the northeastern limit to the western limit the chief workings are known successively as the Green and Defender, Cleveland, 32 cut, Lead adit, West Morrison, and Oxford pits. Other pits and prospect shafts are interspersed between these. The Cleveland mine was not accessible at the time of the investigation. In all these workings the principal development has been at the base of the Rosiclare sandstone, but a few cuts have been made in beds down to and including the "sub-Rosiclare sandstone" horizon. Plate 16 is a map of the principal underground workings.

Ore from open cuts consists largely of residual material in clay, the result of weathering and decomposition of bedding-replacement ore bodies. This material is excavated by steam shovel and sent to the mill for washing. Most of the production during the summer season has come from the open pits, whereas winter operations are restricted to the underground workings. The marketable products are transported by truck to storage bins on the Ohio River at Cave in Rock. The local company office is at Cave in Rock, Illinois.

Green and Defender mines.—The Green and Defender mines are about a quarter of a mile southwest of the Crystal mine. Originally opened through the Defender shaft, these two mines are now operated through adits. The ore bodies are in the Fredonia limestone horizon at the base of the Rosiclare sandstone. The base of the sandstone here consists, as usual, of shale which is the general roof rock of the deposits. At a few spots the mineralized beds exceed 7 feet in thickness, but for the most part the thickness is between 3 and 5 feet. Replacement of the limestone is relatively less complete, and roof fissures appear to be less common, at some of the other mines. The workings of these two mines cover an area approximately 625 feet long and 500 feet wide, but only about half of this area has been mined out. A barren or very low-grade strip crosses this development area in an east-west direction, and is flanked on both sides by belts of higher-grade material, in which all the mining has been carried on. Areas of very low grade or unmineralized ground apparently border the workings on both the north and the south sides, but the widths of these areas have not been determined.

At the adit portal near the east property line the mineralized zone is 3 or 4 feet thick and shows incomplete replacement of cross-bedded limestone. About 20 to 25 feet below this, in the loading cut, weathered exposures of entirely unmineralized limestone clearly display cross bedding.

Cleveland mine and 32 cut.—These openings of the Cleveland mine and 32 cut embrace several adits, drifts, and open pit workings extending northeastward for about a thousand feet, the northeast end being approximately 700 feet southwest of the Green-Defender adit. The mine was not accessible for study. The chief fluorspar bodies were just beneath the Rosiclare sandstone, but sporadic mineralization was found at a lower level.

The 32 cut connects with the southwest end of the underground workings of the Cleveland mine. At this cut an extensive exposure of mineralized cross-bedded sandstone was seen. Typical banded fluorspar was also seen between a sandstone roof and an uneven floor of dense, massive limestone. Comparison of the beds along both sides of the 32 cut and in a small cut on the south side of the roadway suggests a minor fault trending approximately N. 45° E. and a prominent roof fissure of this trend is said to extend throughout the length of the Cleveland workings with which the 32 cut is connected.

The Cleveland mine was opened prior to 1903, by the Cleveland-Illinois Fluorspar Co. Bain,[37] who examined the mine in 1903, states that the ore body was from 18 inches to 6 feet thick, and was found to diminish in thickness northeastward where the workings extended into the hill. He describes the ore as consisting of "interbanded" limestone and fluorite with minor amounts of calcite and galena.

Lead adit.—The lead adit is a short distance west of the Cleveland mine. From its portal, about a hundred feet north of the mill, the workings extend for approximately 1,000 feet in a west-northwest direction. The widest part of the workings is about 350 feet. At the northwest end the drift has been carried about 500 feet southwestward, following a roof fissure, but no stoping has been done along this part of the drift. Two sets of roof fissures are present in this mine, one set trending approximately N. 65° W., and the other N. 45° to 60° E. The mined area covers about 112,000 to 113,000 square feet including pillars. In places mining has been carried to depths of 15 to 20 feet below the main level. Plate 17, *A*, is a photograph of a lower level in this mine.

---

[37] Bain, H. F., Fluorspar deposits of southern Illinois: U. S. Geol. Survey Bull. 255, p. 54, 1905.

A series of cross sections of this mine, showing roof profiles and thickness of mineralized zones, is given in figure 7, and a contour map of the roof is shown on plate 5. The average thickness of ore is from 3 to 5 feet, but considerably greater thicknesses were seen in several

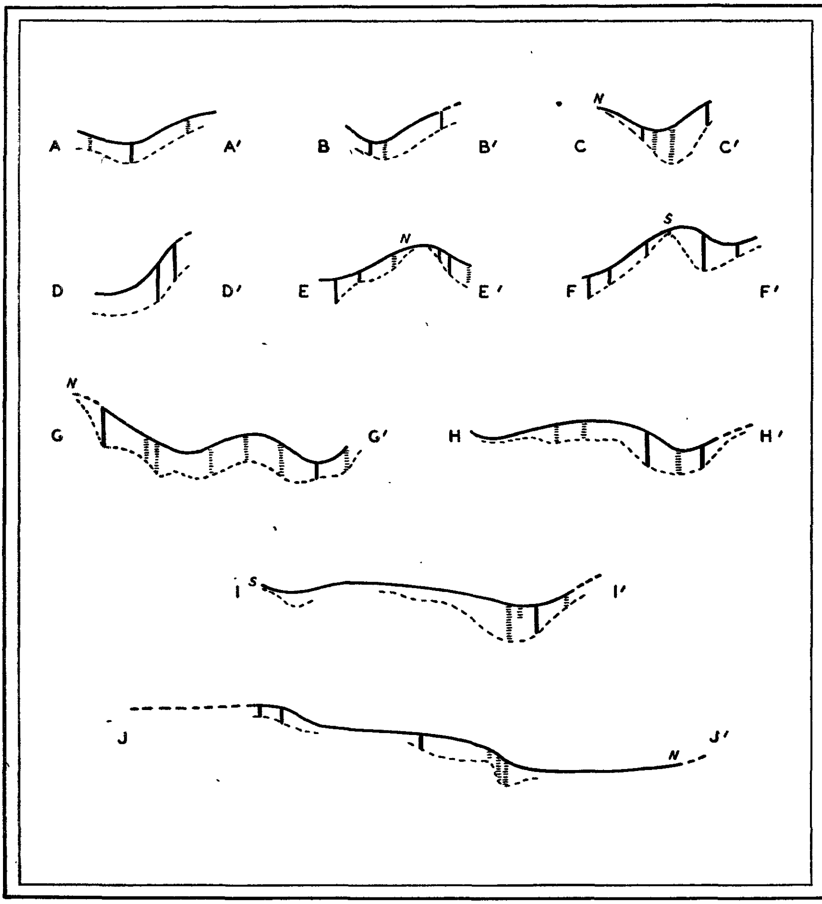


FIGURE 7.—Profiles across Lead adit workings showing relation of mineral bodies to roof slopes. Sections are along lines indicated on plate 5. Vertical scale 5 times horizontal scale. Heavy vertical lines indicate measured thicknesses of mineralized zone at points on or close to section line; hachured vertical lines indicate measurements intermediate between sections; solid lines indicate top of mineralized zone (base of Rosiclare sandstone member); dashed lines indicate interpreted base of mineralized zone; S, points of streaky or slight mineralization; N, points of practically no mineralization.

places. The thicker bodies occur beneath steep dips of the roof, and seem to be near or along the axes of pitching synclinal troughs.

The thinning of banded fluorspar between the shale roof and the massive floor limestone is well shown in the exposures at the adit portal (see pl. 13, *B*).

West Morrison adit and open cuts, and Oxford pits.—The West Morrison adit is about 850 feet slightly south of west from the Lead adit portal. The adit and open cuts extend southwesterly from this point about 850 feet to the Oxford pits. At the adit very little development has been done; from 3 to 4 feet of fluorspar containing an appreciable amount of unreplaced carbonate appears beneath a shale roof in which there is a roof fissure trending N. 45° E. The pits are in a residual "gravel" deposit, with blocks of fluorspar resting in thick surface clay mantle, derived from original bedding-replacement ore at the Rosiclare sandstone horizon. To the southwest a mineral zone 20 to 25 feet below this horizon has yielded some ore.

The Oxford pits, essentially a continuation of the West Morrison pits, obtain material from a disintegrated zone extending through a range of 30 to 40 feet, between the Rosiclare sandstone and "sub-Rosiclare sandstone." At the south Oxford pit the contact between the "sub-Rosiclare sandstone" and the overlying dense limestone pitches to the northeast, about 10 feet in 100, and at the northeast it dips below pinnacles of the dense limestone, around which "gravel spar" occurs.

The highly calcareous nature of the markedly cross-bedded "sub-Rosiclare sandstone" is well displayed in fresh cuts at this locality. The layers of this rock vary from calcareous sandstone to sandy limestone, with the sandstone facies predominating.

Prospect shafts east of Green-Defender mine.—The Benzon Fluorspar Co. has recently prospected on the crest and sides of a low knoll, 1,500 to 2,000 feet east of the Green-Defender workings, in the lowlands (East Green prospect on pl. 1). The "sub-Rosiclare sandstone" appears near the top of this knoll and has been penetrated by several prospect shafts and drill holes. A considerable thickness of fluorspar, largely in a clay and sand matrix, and resting on an irregular limestone surface, has been reported.

Victory Fluorspar Mining Co.—The properties of the Victory Fluorspar Mining Co. (post office address, Elizabethtown, Ill.) are situated north of the property of the Benzon Fluorspar Co., on the nearly level top of Spar Mountain, just north of the escarpment.

The workings are all underground and comprise approximately 4,000 feet of drifts and cross cuts, besides many large irregular rooms. The company operates two shafts, the older of which, No. 1, is near the east end of the property, and the other, No. 2, about 1,100 feet west by south of No. 1. The workings from the two shafts did not connect in 1935. Up to 1937, most of the drifting and mining has been done in No. 1 mine, but No. 2 mine was being developed with a view to connecting it soon with the other. The drift map of No. 1 mine as it was in 1934 is shown is figure 8. The company has built a new mill of 150-ton capacity per 8-hour day at the No. 2 shaft; a flow sheet of this mill is given in plate 18.

The shafts reach the ore horizon at the base of the Rosiclare sandstone, at depths of about 145 and 130 feet, respectively. For the most part underground development has followed the ore bodies, but in addition several long drifts have been driven with a view to developing a retreating method of mining. The area opened up by the No. 1 mine was about 500 feet square in 1934.

The thickest mineral bodies occupy the sharper folds, particularly where the pitch of the roof is steepest, but two broad areas of this mineralized ground underlie parts of the roof that are low and flat. The average thickness of the developed ore bodies is probably

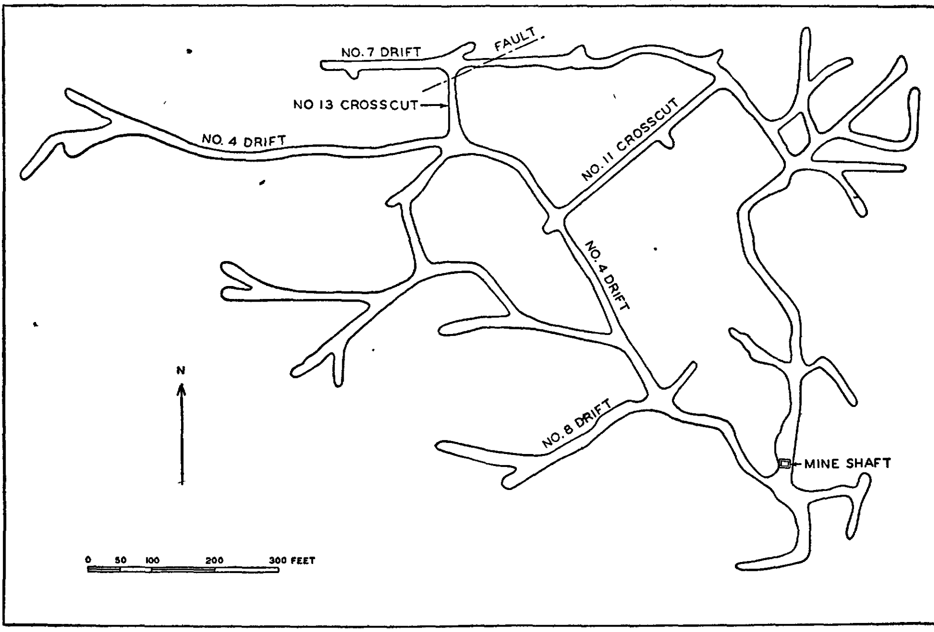


FIGURE 8.—Map of drifts in Victory No. 1 mine. Courtesy of Victory Fluorspar Mining Co.

between 5 and 6 feet, with a maximum thickness of approximately 12 feet. Plate 17, *B*, is a photograph of an ore face. So far, only the Rosiclare sandstone horizon has been explored. Roof fissures are present but have not been used as "leaders" in this mine.

No. 1 shaft has been sunk within a comparatively large area of barren or low-grade material, but about 150 feet north of the shaft, the roof pitches steeply northward and the fluorspar body thickens somewhat abruptly. About 200 feet north of the shaft from 3 to 5 feet of fluorspar was found, and the mineral zone thickens to 7 feet a short distance beyond this point, as the roof rises sharply on the limb of a narrow, pitching anticline whose axis trends about N. 70° W. Excellent ore was seen for the greater part of 200 feet. Drifts running westward to northwestward from the shaft followed this ore along a stretch where it was comparatively thin, being under a level part of the roof, but reached a thick body at a distance of approximately 350 feet from the shaft, where the roof rises markedly to the southeast and the contours indicate local warping. From 50 to 75 feet north of this point, however, the roof is low and exceptionally level through a width of 100 feet, and here the mineralized zone is thin. At a point 100 feet southwest of the shaft and for 200 feet west-southwest, the roof slope was again seen to rise abruptly and two small but thick (5 to 7 feet) ore bodies were found. It thus appears helpful to watch the dip of the roof closely as a guide in development.

At one place on an east-west drift along the northern border of the workings a small fault trending N. 70° E. and dipping 83° to the north by west, was observed. The fault is of postmineral origin, as is shown by brecciation and pulverizing of the fluorspar body it crosses; striations on the slickensided surface indicate a nearly horizontal displacement.

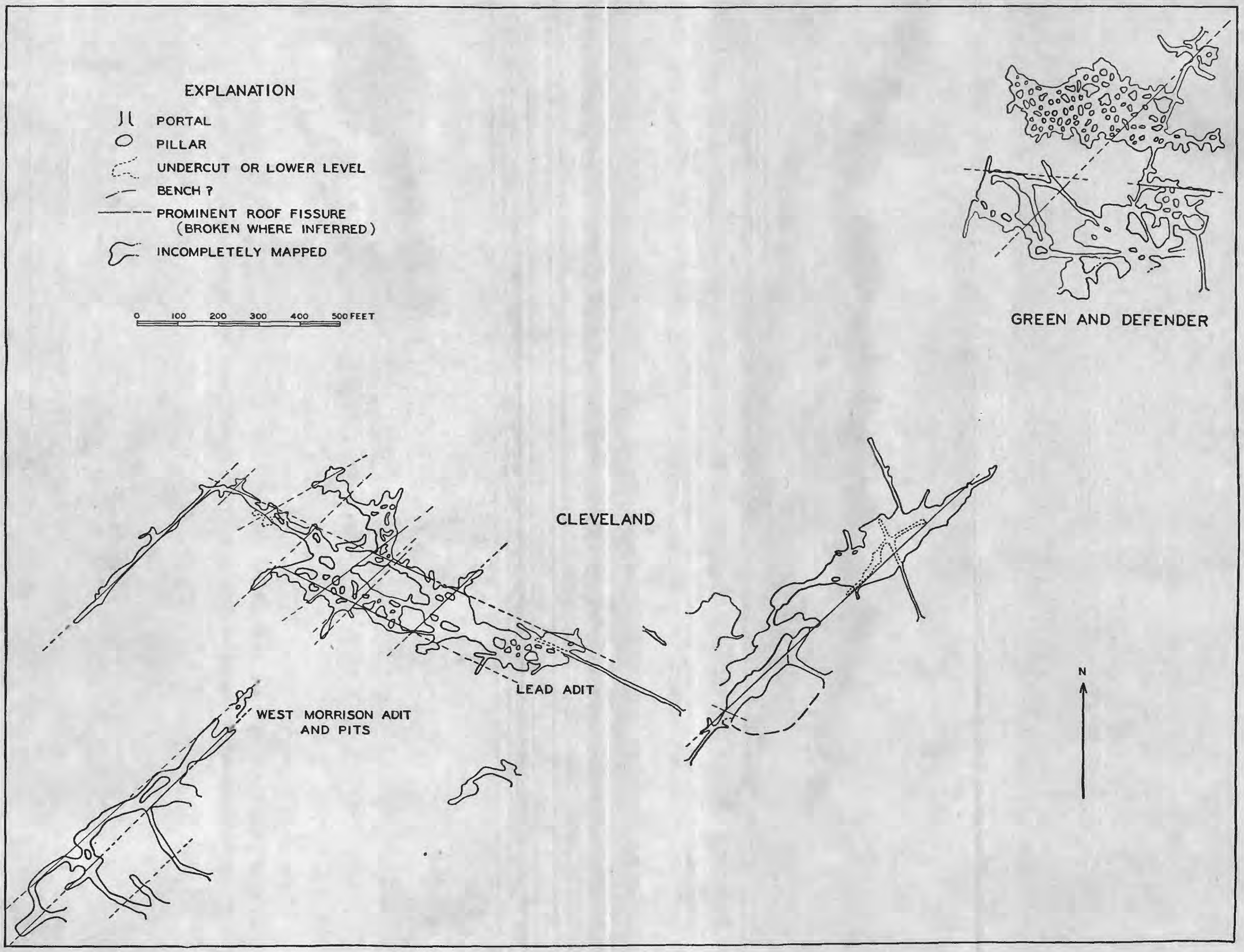
At several places, particularly in No. 2 mine, flat cavities at the top of the ore body are lined with large crystals of fluorspar, some cubes of which show faces several inches across. In some places thin seams of clear crystalline purple fluorspar penetrate the shale roof parallel to the bedding. (See pl. 15, *B*.) Barite was seen at several places, but it is not abundant or conspicuous in the mine.

At several places in No. 1 mine, beds of dense, brown limestone, an inch to a foot or two thick were seen to separate beds of typical "coon-tail" fluorspar. In general such limestones appear to have been replaced only slightly or not at all, while adjoining beds of more porous texture and variable crystallinity were replaced by bodies of high grade ore. It is common for several thick layers of well-layered fluorspar, showing cross-bedding structure, to be separated by thin partings of dense brown limestone or shale which range in thickness from a fraction of an inch to several inches but are usually not more than 3 inches thick.

Cave in Rock mine.—The abandoned Cave in Rock mine is situated at the base of the southwest slope of Spar Mountain, about 1,200 feet northwest of the Oxford Pits of the Benzon Fluorspar Co., in the NW.¼ NE.¼ sec. 4, T. 12S, R. 9 E. Adits have been driven into the slope at two levels, one at the base of the Rosiclare sandstone, and the other at the horizon of the "sub-Rosiclare sandstone," which at this locality is about 40 feet lower. The workings were not accessible, but a brief description of them has been given by Bastin.[38]

A fault of north by west trend (fault No. 10, pl. 1) appears to be intersected by the lower workings, and probably also by the upper workings. In the lower workings the cap rock appears to be a dense

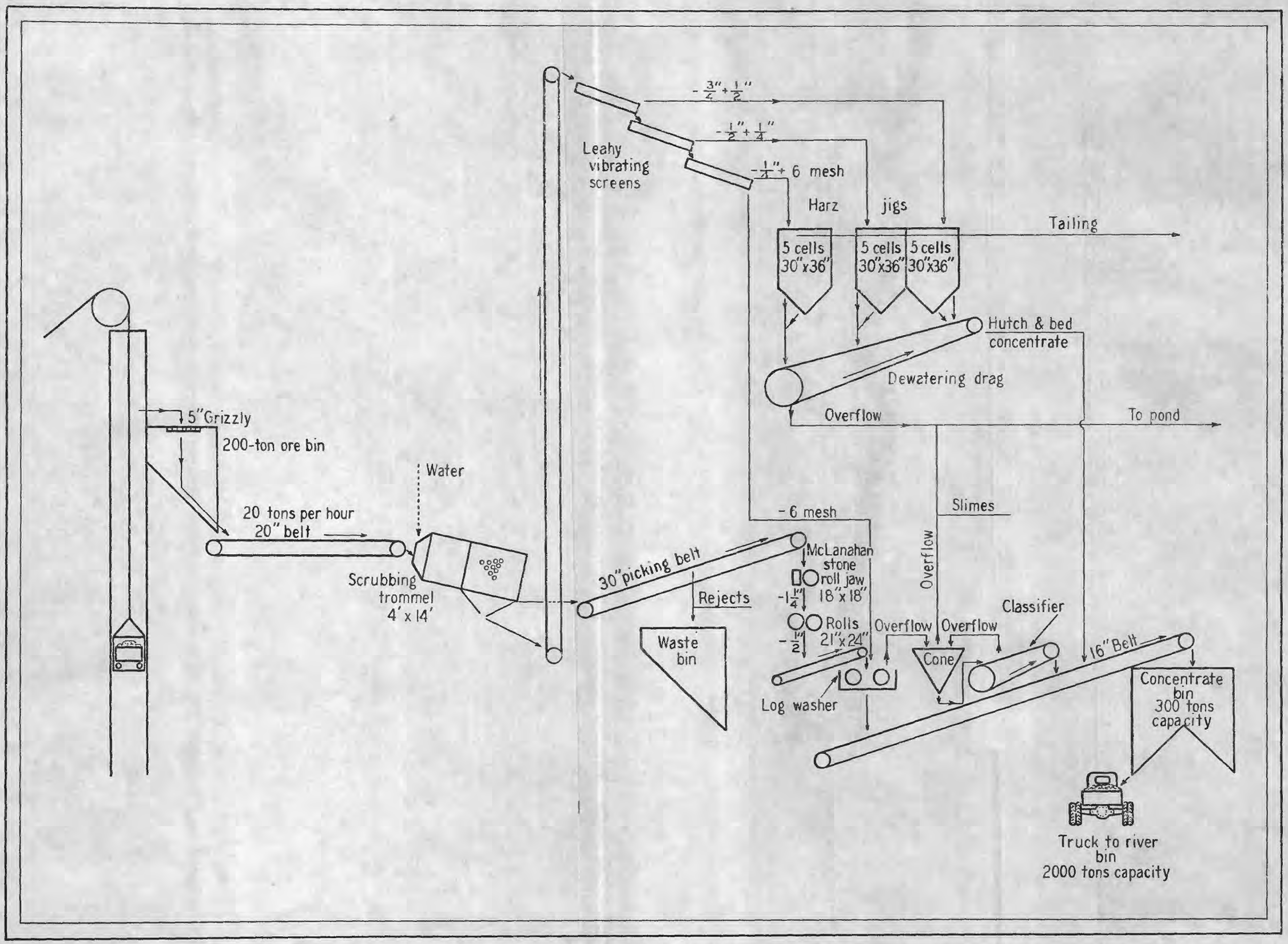
[38] Bastin, E. S., The fluorspar deposits of Hardin and Pope counties, Ill.: Ill. Geol. Survey Bull. 58, pp. 92–93, 1931.



MAP OF PRINCIPAL UNDERGROUND WORKINGS OF BENZON FLUORSPAR CO.
Courtesy of J. W. H. Blee.

A. TWO LEVELS OF MINERALIZATION IN LEAD ADIT.

B. FACE OF BANDED FLUORSPAR IN VICTORY NO. 1 MINE.



FLOW SHEET, VICTORY FLUORSPAR MINING CO.'S MILL.
Courtesy of Victory Fluorspar Mining Co.

siliceous bed, either a completely silicified limestone, or the completely quartzitized "sub-Rosiclare sandstone." The ore body was apparently 1 to 4 feet thick, but in much of the dump material fluorite layers alternate with layers of crystalline quartz. Considerable galena is said to have been found here in pockets. So far as could be judged from surface observations, this mine appears to be partly at least, in a local zone of silicification, probably closely connected with a fault fissure. The silicification of the cap rock and of the mineral body appears to be somewhat similar to that found at the Miller mine (now abandoned) on the west side of Lead Hill, and to certain prospects on the east side of the hill.

Pittsburgh Fluorspar Products Co.—The Pittsburgh Fluorspar Products Co., of Pittsburgh, Pa., operates property on the south end of Lead Hill. The workings consist of several adits and short, irregular drifts on the east and south sides of the hill, near the top. The fluorspar is mined chiefly at the base of the Rosiclare sandstone, but some exploratory adits have been driven at levels about 40 feet lower. The ore is of the usual "banded" variety. Although the ore bodies are comparatively thin, some very high-grade material has been obtained. In a typical specimen of ore from one of the upper adits layers of pure, coarsely crystalline fluorspar 2 inches thick and showing comb structure alternate with fine-grained impure bands, half an inch thick. The ore from these deposits lacks the conspicuous quartz layers that are in much of the material found farther north on Lead Hill.

At the No. 1 adit, where the Rosiclare sandstone forms the roof rock, the immediate cap rock consists of about 2 feet of shale. Near the portal the underlying limestone is well bedded and breaks in plates about 1 to 3 inches thick, with thin shaly partings. From 1½ to 2 feet of high grade fluorspar was seen in this opening, and the pure layers greatly exceed the impure layers in thickness (see pl. 11). At the face two diverging "runs" of ore followed distinct sags in the roof, and several veinlets in the roof followed the axis of the sag above the thickest part of the mineral body.

At No. 2 adit, about 100 feet south of No. 1, the shale cap rock attains a thickness of 4 or 5 feet and pitches to the north. The fluorspar body thickens down the dip of the roof. Bedding veinlets occur in the lower part of the shale cap rock.

At No. 5 adit on the south side of the hill the cap rock is a dense limestone bed that lies 40 feet below the base of the Rosiclare sandstone. The adit follows a central roof vein in a sag, and trends N. 20° E. This vein has a maximum thickness of 3 inches and was followed from the surface exposure. At the face of the adit coarse-grained vein material was seen to extend from the floor to the roof. The vein widens toward the roof, and bedding-replacement fluorspar extends from the vein laterally below the capping, but this bedding material averaged only a few inches in thickness.

At the portal of a new adit on the southeast side of the hill, about 41 feet below the Rosiclare sandstone there obviously has been replacement along bedding planes of the limestone. The mineralization at this point is slight to incipient and definitely shows penetration along bedded and cross-bedded limestone, in part extending from a mineralized minor joint plane. A layer of thin-bedded limestone 4 to 12 inches thick is more strongly mineralized than more massive beds above and below. Both fresh and weathered limestone show considerable variation in texture, and thickness of individual layers.

C. M. Miller mine (abandoned).—The abandoned C. M. Miller mine, operated last by the Basic Mineral Co. of Pittsburgh, Pa., is situated on the west side of Lead Hill, about 500 feet west by north of the No. 1 adit of the Pittsburgh Fluorspar Products Co.'s workings. The mine was inaccessible at the time of this investigation, but the workings have been briefly described in earlier publications.[39] Present exposures at this locality show considerable silicification of limestone. Bastin reported as follows:

Several small branching drifts and small pits develop a replacement deposit, similar in general type to the deposits at Spar Mountain, in Fredonia limestone not far below the Rosiclare sandstone.

Within a zone about six feet thick occur two or three flat-lying replacement zones of fluorspar ore as much as 1½ feet thick and parallel to the bedding. * * * In some vugs crystals of white quartz as much as one-half inch across appear to have formed contemporaneously with the fluorite, and in others it encrusts fluorite crystals and is clearly younger. Galena is of spotty distribution but may form masses three to four inches across.

In 1917 the present writer made the following observation in workings that are now caved:

Near the entrance to the northern end of the two tunnels running into the hill, the horizontal mass of fluorspar is seen to pass downward, funnel-shaped, into a narrow vein, which evidently represents the channel followed by the ore-bearing solutions.

Miscellaneous prospects.—Several other prospect shafts and adits are distributed over the west and east sides of Lead Hill and in the topographic saddle between Lead Hill and Spar Mountain (see pl. 3), but little was learned from them, for in 1935 none of them had been developed to the producing stage and all were inaccessible.

At a prospect (the Chester Martin?) part way up on the east side of Lead Hill a bedding-replacement deposit has been exposed below a roof of massive, blocky, dense limestone. A persistent layer of chert 2 to 3 inches thick forms the immediate cap rock of the deposit,

[39] Bastin, E. S., op. cit., p. 94. Currier, L. W., in Weller, Stuart, and others, The geology of Hardin County, Ill.: Illinois Geol. Survey Bull. 41, pp. 300–301, 1920.

which is about 4 feet thick. The alternate layers are siliceous and consist in large part of quartz crystals. Some of the limestone below the chert shows prominent silicification.

MINING METHODS

The methods of mining the bedding-replacement deposits are simple as compared with the vein deposits and entail no particular difficulties. Where the deposits are exposed along a slope, they are entered through horizontal adits, from which drifts, crosscuts, and irregular rooms are developed. Generally these openings follow the mineral bodies, avoiding the lean or barren material so far as possible, and leaving pillars for support as needed. After a mine has been worked out it is planned to retreat to the portal, removing such pillars as contain ore. The procedure thus resembles the retreating method utilized in coal mining. Because of the general practice of mining to the economic limits of ore bodies, and first following the richer runs, and because of the structural characteristics of the ore bodies, the rooms and drifts are not developed according to a definite pattern or with regular spacing.

The practice, in some mines, of following roof veins as "leaders" has already been mentioned. There appears to be a geologic foundation for this practice, and probably further attention should be paid to the relation of ore bodies to roof contours, especially with regard to the advisability of developing exploratory crosscuts toward the structural low points in the roof flexures.

Where the ore horizon is not exposed at the surface, vertical shafts are sunk, from which drifts and rooms are developed. In these workings also a retreating method is generally planned, but economy forces the operator to develop a larger area in shaft mining than in adit mining before the pillars are removed.

Very little timbering is required in underground operations as practiced in this district. The amount of underground water encountered, also, is very small and presents no particular difficulties. In deeper mining further northeast, however, greater quantities of water will doubtless be met, increasing the costs of operation.

Deposits of "gravel" fluorspar in surface clays are mined by open-cut methods, and a steam shovel is serviceable in places.

MILLING METHODS

Milling fluorspar ores low in silica from the bedding-replacement deposits is a comparatively simple process. The constituents of the ores are chiefly fluorspar, limestone, and clay, though very subordinate amounts of shale and sandstone also find their way into the mill heads, and these rocks contain most of the silica that is in the crude ores.

Sulfides have so far been too rare to affect the design of flow sheets. As the minerals of the ores are mostly coarse-grained and relatively free, simple methods of crushing and classifying serve to separate the mineral components sufficiently for economical concentration.

By careful selection in the mines, much material has been obtained that required simple washing to remove adhering clay, but the usual practice, regarded as more economical, is to send all the mine product

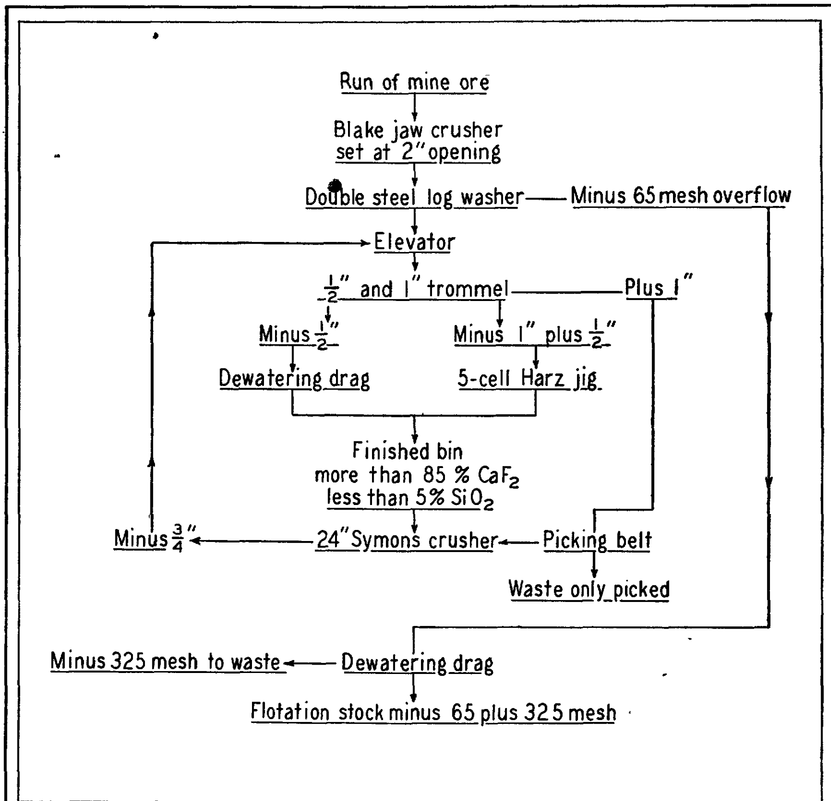


FIGURE 9.—Flow sheet, Crystal Fluorspar Co.'s concentrating mill. Courtesy of Crystal Fluorspar Co.

to the mill for coarse crushing and washing, and then to remove the waste from the oversize product of the washing trommel by hand picking from a picking belt. The cleaned and picked material is then crushed and, together with the trommel undersize product, sized and sent to concentrating machines. Details of operations at the three mills of the district are shown in figures 9 and 10 and plate 18, the data for which were kindly furnished by the respective operators.

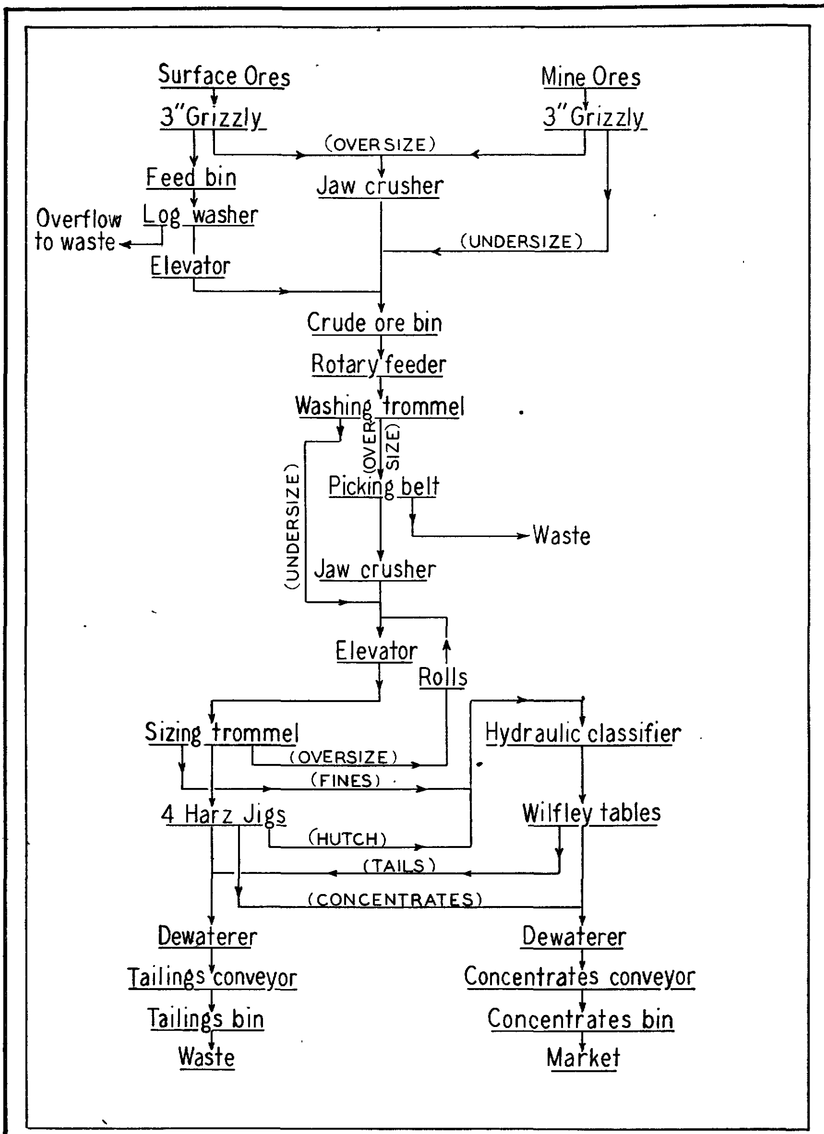


FIGURE 10.—Flow sheet, Benzon Fluorspar Co.'s concentrating mill. Courtesy of Benzon Fluorspar Co.

ECONOMIC CONSIDERATIONS [40]

USES AND GRADES

The uses and market grades of fluorspar have been described in earlier publications [41] and need to be only briefly reviewed here for the purpose of showing the general adaptability of the Cave in Rock ores to the chief industrial requirements.

The principal use of the fluorspar is as a metallurgical flux in the production of steel by the basic open-hearth process. For this purpose admixed calcite is not objectionable, and a moderate amount of silica is allowable; silica, however, reduces the available effective units of calcium fluoride in the flux, so that a standard maximum content is generally specified. Sulfur, even in very small amounts, is objectionable, and, if sulfide minerals and barite are present in the ore they must be largerly eliminated by milling. Metallurgical fluorspar is generally required to be in "gravel" form, and the standard gravel spar is composed of fragments less than 1 inch in diameter; "fines" are objectionable because of excessive losses in the flues brought about by the furnace drafts. On the other hand, fluorspar that is too coarse is not readily assimilated. For these reasons a standard size range is specified. Metallurgical fluorspar is used also in the manufacture of "electric-steel" and ferroalloys, and in foundry work, but only a small proportion of the metallurgical fluorspar produced is used for these purposes. Most of the Cave in Rock ores mined up to the present time have been milled easily to produce standard fluxing spar, for their fluorspar content has been high, their calcium carbonate and silica contents correspondingly low, and their sulfur content negligible; moreover, fine crushing has not been necessary.

Where a large amount of sphalerite is present, as in deposits recently discovered and opened (1937 and 1941, see Addendum, p. 71) in the northeastern part of the area, a special milling process is required to separate the fluorspar and the zinc sulfide; a flotation method is used for this purpose and it requires fine grinding of the ores, but it permits adequate separation of the minerals to give a high-grade fluorspar concentrate that may be of "acid" grade, as well as a zinc concentrate. For use as a flux in the steel industry the fine-grained fluorspar product of the flotation process requires sintering and pelletization.

---

[40] Although no attempt has been made to bring this report as a whole up to date (May 1943), some data regarding market grades of fluorspar production and recent references have been added to this and the succeeding section on reserves.

[41] Bastin, E. S., The fluorspar deposits of Hardin and Pope Counties, Ill.: Ill. Geol. Survey Bull. 58, pp. 101–104, 1931. Ladoo, R. B., Fluorspar, its mining, milling, and utilization: U. S. Bur. Mines Bull. 244, 1927. U. S. Bur. Mines, Mineral Resources U. S., 1926, pt. 2, pp. 30-34; Minerals Yearbook for years 1935 to 1940, and 1941 (Review of 1940), chapters on fluorspar and cryolite. Hatmaker, Paul, and Davis, H. W., The fluorspar industry of the United States, with special reference to the Illinois-Kentucky district: Illinois Geol. Survey Bull. 59, 1938.

For use by the chemical and alumium industries fluorspar of particularly high grade is required. Both silica and sulfur-bearing minerals are very objectionable, and even calcium carbonate is undesirable because of its frothing action. Standard specifications for "acid spar," the grade used for these purposes, have required at least 98 percent of CaF_2 and not over 1 percent of SiO_2. Though the richer parts of some of the ore bodies in the Cave in Rock district have often yielded very high grade ore, suitable for the production of "acid spar," some of the ores, particularly from the margins of ore bodies, have required mixing with high grade ore in order to meet the requirements for standard metallurgical fluorspar, and consequently most of the fluorspar marketed from this district has been of metallurgical grade.

The ceramic industry uses fluorspar in the manufacture of certain glasses and enamels, and for these purposes ground fluorspar that contains at least 95 percent of CaF_2 and not over 3 percent of SiO_2 is considered standard.

The chief commercial grades of fluorspar as of 1940 are summarized in the following table, quoted from U. S. Bureau of Mines, Minerals Yearbook, Review of 1940:

Grade	Form	CaF_2 (minimum percent)	SiO_2 (maximum percent)	Fe_2O_3 (maximum percent)
Metallurgical	Washed gravel, less than 1 inch and not more than 15 percent fines.	85	5	
Ceramic	Glass and enamel	95	3	0.12
Acid	Lump, gravel, and ground	98	1	

Current market prices have been based upon these grades, but the specifications as given above have not been strictly adhered to, particularly with respect to metallurgical spar, for some consumers have accepted as fluxing spar material that contained as low as 80 percent of CaF_2 and as high as 6 percent of SiO_2, the price being adjusted accordingly.

PRODUCTION

Prior to 1919 production from the bedding-replacement deposits of the Cave in Rock district was intermittent and inconsiderable in comparison with the total production of the Illinois-Kentucky field. Since that year, as a result of more consistent development of old properties, and exploration and development of new ones, the district has gained rapidly in importance as a producer of fluorspar, and it is likely to make a considerable further production in the future.

The purity of much of the Cave in Rock ores and the low cost of mining and milling them as compared with many of the vein deposits gave a distinct economic advantage to the district in its earlier days, and it seems fairly probable that in the future it will be possible to extend operations over a much larger area, thus materially increasing the reserves, and that the district will, for some time, become increasingly productive. The production of fluorspar in this district by years since 1919, as compared with the total production in Illinois and the United States, is shown graphically on plate 19.[42] The data upon which these curves are based represent shipments rather than actual production, so that for any single year only approximate production is indicated; the difference, however, from actual production figures is probably small. Over a period of 2 years or more the accordance will doubtless be close, and the curves will therefore give a fair idea of the relative industrial importance of the district.

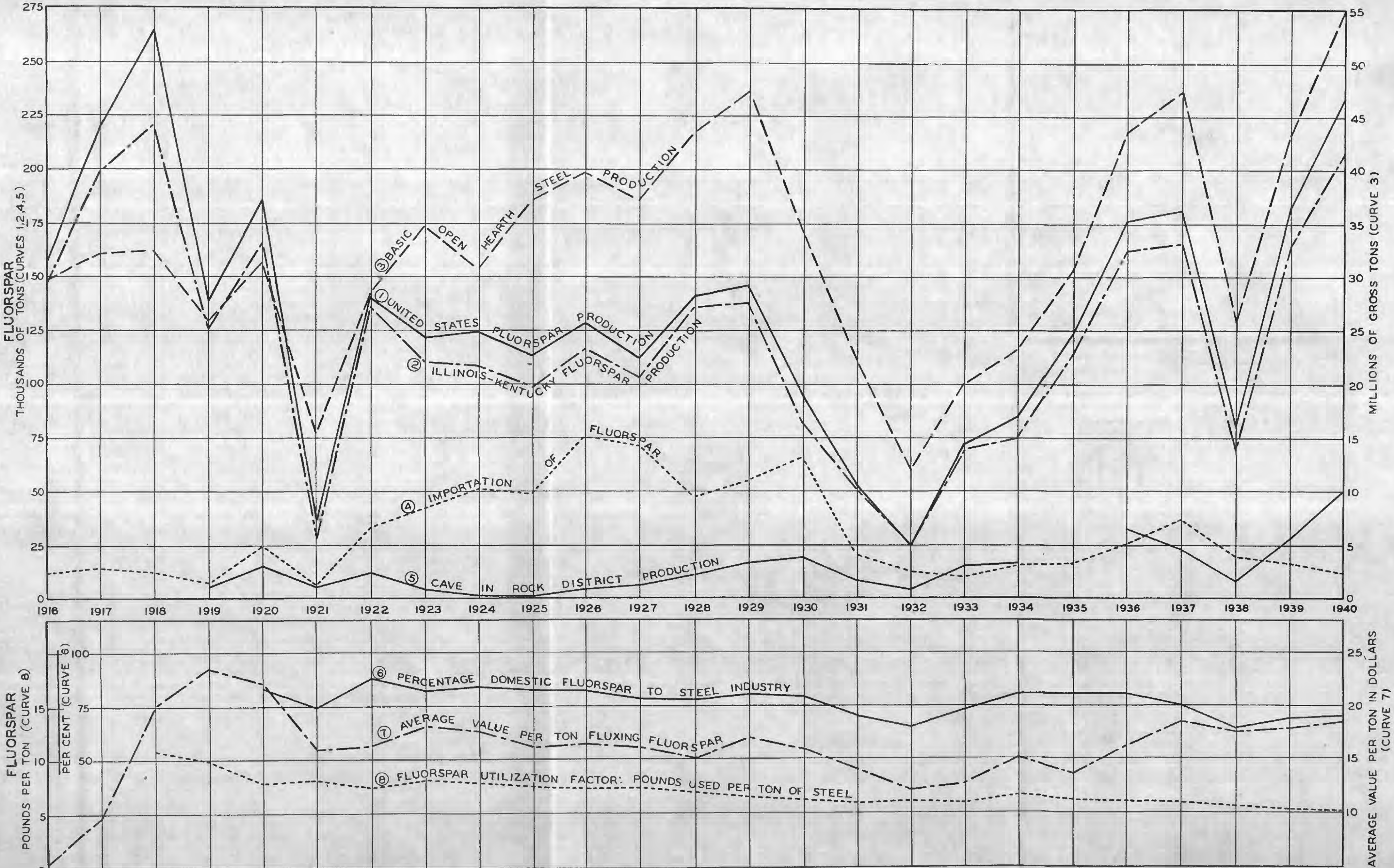
RESERVES

Owing to lack of extensive development and of sufficient exploration in advance of mining, it is impossible to compute the reserves of the district in the usual manner, but the structural and genetic relations of the deposits, and the geologic features of the district seem sufficiently clear to justify a rough estimate based on reasonable assumptions and on the extrapolation of certain calculated factors. The four primary factors that enter into the estimation of fluorspar reserves in the Cave in Rock district are (1) area of geologically favorable territory, (2) percentage of that area that is mineralized, (3) average concentration of fluorspar in mineralized ground, and (4) average percentage recovery of marketable fluorspar from mineral bodies of the bedding-replacement type.

These factors cannot be evaluated closely. In particular, the extent of the mineralized ground and the average concentration of fluorspar in that ground are determinable only from data to be obtained through extensive and well-distributed underground exploration. An estimate of possible reserves in the mapped area was made in 1936.[43] It seemed probable, when the known major geologic features were viewed according to the theory of origin (presented in this report) that between 900 and 1,000 acres of the mapped area were favorable to the deposition of fluorspar ore. Less than a third of this area, however, had yielded specific data for evaluating the factors involved in the calculation of possible reserves. The factors thus derived were applied to the remaining two-thirds or more of the area, and a reserve of 500,000 to 700,000 tons of marketable fluorspar was thus calculated for the area mapped. It was pointed out, however, and is reaffirmed here, that this estimate was based largely upon geologic interpretation, and that its chief value would probably consist in the stimulus it might give to prospecting and exploring in the undeveloped parts of the district.

[42] This set of curves has been brought up to 1940 since preparation of this report.

[43] Currier, L. W., Geologic factors in the interpretation of fluorspar reserves in the Illinois-Kentucky field: U.S. Geol. Survey Bull. 886-B, p. 13, 1937.



GRAPH SHOWING PRODUCTION AND UTILIZATION OF FLUORSPAR, 1916–40.

ADDENDUM

Since the field work that forms the basis of this report was completed, in 1935, several significant developments have taken place in the Cave in Rock district. It has not been possible to do further field work in order to bring the body of the report up to date, but it is desirable to add a brief summary of the significant data recently acquired from various sources.

According to available data[44] about 300,000 tons of fluorspar have been shipped from the Cave in Rock district from the beginning of 1936, when the above reserve estimate was made, to the end of 1942. Most of this production has come from properties that were being operated in 1936, but a considerable part has come from a deposit discovered in the northeastern part of the mapped area since the field study for this report was made. Another large deposit recently discovered and explored northeast of the mapped area has greatly extended the district and is expected to greatly increase the potential reserves.

In 1937, shortly after the completion of this report, the Mahoning Mining Co. acquired options on a tract of land in the northeastern part of the area as mapped for this report. The property was prospected by drilling to a depth of 300 to 400 feet. A shaft 300 feet deep was sunk at a point in the NW¼ NE¼ sec. 34, about 3,500 feet north of the Crystal mine adit, and near faults 16 and 17 (see pl. 3) in an area where both surface geologic data and resistivity data indicate structural features favorable to mineralization. It is reported that mineralized beds have been found on this property in the Renault formation, in the top of the Fredonia limestone, and in the "sub-Rosiclare sandstone," about 60 feet below the base of the Rosiclare sandstone member; the "sub-Rosiclare" is said to contain the main ore body. The ore bodies here are composed of alternating layers of rather coarsely crystalline fluorspar and sphalerite. Both minerals are recovered by flotation at the company's mill in Rosiclare. The ore bodies appear to be closely associated with two minor faults about 100 to 120 feet apart. The company has also sunk three shafts to other bedding replacement deposits in the northwest and northeast quarters of section 35, east of the W. L. Davis shaft; at two of these places the mineralized horizons are said to be in the upper parts of the Renault formation and the Fredonia limestone.

Another recent development of considerable significance is that of the Minerva Oil Co., which has drilled extensively in an area consisting

[44] U. S. Bur. Mines, Minerals Yearbook for years 1937 to 1940, inclusive. H. W. Davis, personal communication, May 8, 1942.

of 3,000, acres that lie northeast of the W. L. Davis mine. According to a summary report of the Bureau of Mines[45] more than a hundred holes have been drilled here, and 311,000 tons of ore containing 5.47 percent of zinc and 37.1 percent of fluorspar and 219,000 tons of ore containing 3.33 percent of zinc, 20.53 percent of fluorspar, and 0.56 percent of barite are indicated. The ore is said to occur as bedding-replacement deposits in the Renault formation, the Levias limestone, and the top of the Fredonia limestone. A shaft is being sunk to a depth of about 640 feet, where it will presumably reach into or through the Levias limestone. The shaft is located approximately at the center of the southeast quarter of section 24, nearly three miles northeast of the Crystal mine adit.

In 1936 the workings of the Crystal mine were at the top of the Fredonia limestone, and the shale base of the Rosiclare sandstone formed the cap rock of the bedding-replacement deposits that constituted the ore body. Since that year, not only have the original workings been greatly extended to the northeast—the length in this direction being now 1,750 feet—but crosscuts to the northwest have reached a second ore body parallel with the first; moreover, ore is reported to be obtained at several levels in the upper 45 feet of the Fredonia limestone, and at the "sub-Rosiclare" horizon. A small amount of ore is reported to occur also in the Renault formation.

According to the data cited above, the recently discovered deposits occur at the same stratigraphic horizons as those previously studied in the area mapped; that is, in the uppermost beds of the Fredonia limestone member, in the "sub-Rosiclare sandstone," and in the limestone beds of the Renault formation. In addition the Levias limestone member is said to be mineralized in places. Details of structural control in the newly developed areas are not known, but it is clear that in part, at least, the deposits are closely associated with minor faults, and that these faults and the longer dimensions of the mineral bodies trend approximately parallel with the Peters Creek fault zone—the principal axis of regional deformation—although quite remote from this zone.

The discovery of bedding-replacement deposits in the southeastern quarter of section 24, nearly 3 miles northeast of the crystal adit and nearly a mile and a quarter from the Peters Creek fault zone, has definitely extended the area to be recommended for prospecting considerably beyond the limits of the mapped area. Such deposits, and consequently favorable structural conditions are thus known to exist through an area of at least five square miles, all of which is worthy of serious consideration. A detailed geologic and geophysical investigation is recommended.

[45] U. S. Bur. Mines, War minerals report No. 118, Zinc-fluorspar property of the Minerva Oil Co., Cave in Rock, Hardin Connty, Ill., October, 1942.

Part 2. AN EXPLORATORY STUDY OF FAULTS IN THE CAVE IN ROCK AND ROSICLARE DISTRICTS BY THE EARTH-RESISTIVITY METHOD

By M. KING HUBBERT

ABSTRACT

This report is a presentation of the results of an electrical-resistivity survey conducted in the fluorspar-bearing areas of Hardin County, Ill., principally during the field seasons of 1934 and 1935. Gish-Rooney apparatus employing the Wenner 4-electrode method of measurement, was used. Traverses were run in directions usually transverse to the strike of the dominant systems of faults. In all but two short profiles, the electrode spacing was 100 feet with the measurements made at 100-foot intervals. The line of electrodes was parallel to the line of traverse.

Most of the work was done in two districts, one near the town of Rosiclare and the other in the mining district northwest of Cave in Rock. In many cases the presence of faults was clearly indicated. A fault was mapped for a distance of about 2 miles in the alluvium-filled valley of Wallace Branch, about 3.5 miles west of Rosiclare. Some of the branches of the Peters Creek fault in the Cave in Rock district were clearly shown. In many other instances anomalies appeared, the causes of which were not evident, but they may be related to structural disturbances.

One curious anomaly was discovered at station 83.5 on profile 13 in the Rosiclare district. It suggests an unusual subsurface condition, which warrants further consideration.

In the Cave in Rock district a region of marked disturbance was indicated in the northeast part of the resistivity grid, suggesting the possibility of complex fracturing of small displacement favorable to the infiltration of mineralizing solutions. This locality is indicated as being one of the most hopeful prospects of the territory surveyed.

Although the significance of many of the observed anomalies is not clear, it is possible that their existence may provide useful clues for the guidance of direct prospecting. With this in view, not only have the author's own interpretations been presented, but the direct measurements themselves have been plotted in graphical form.

INTRODUCTION

One of the principal fluorspar-producing regions of the world is located in southern Illinois and western Kentucky. Except for a small area in Pope County, the Illinois portion of this Illinois-Kentucky field is in Hardin County, and the Rosiclare and Cave in Rock districts, dealt with in this report, are in that county.

Hardin County is bounded on the south and east by the Ohio River (see fig. 1). Its topography is rather broken, with elevations ranging from 350 to more than 700 feet above sea level. The geologic formations exposed in the county are principally sedimentary, though there are several small intrusions of igneous rocks in the area. The outcropping sedimentary rocks range in age from Devonian to Carboniferous. They are partly covered with wind-blown loess over the uplands and stream alluvium in the valleys. The rocks are described in part 1 of this report, and the stratigraphic sequence is shown in figure 3.

CLASSIFICATION OF ROCKS ON THE BASIS OF PHYSICAL PROPERTIES

For the purposes of the present investigation the stratigraphic column of the area falls into three principal subdivisions, based upon the physical properties of the rocks. The lowest of these divisions extends up to the top of the Fredonia limestone. It is characterized by hard, massive, electrically-resistive rocks—limestone, chert, and shale. The middle division extends from the top of the Fredonia limestone to the bottom of the Pottsville group. Owing to successive repetition of sandstones, shales, and limestones, its physical properities are variable. The upper division extends upward from the base of the Pottsville group. The sandstones of the Pottsville are massive and are highly resistive to the flow of electricity. They form the highlands of the county and frequently crop out as bluffs.

Most of the work for the present report has been done in areas containing outcrops of formations of the middle division and of the upper part of the lower division.

Structurally, Hardin County is chiefly characterized by an intricate system of normal faults, which cut the sediments into a mosaic of slightly tilted fault blocks in which the dip of the beds commonly ranges from 0° to 15°. Most of the major faults strike northeastward, and the blocks between them are cut by shorter transverse faults into many small irregular segments.

Isolated occurrences of fluorspar are found in all parts of the county, but the greater part of the mining production has come from two rather small areas. One of these, called the Rosiclare district, is in a faulted belt that extends 3 miles in a direction about N. 30° E. from the Ohio River through the west edge of the town of Rosiclare. The second is called the Cave in Rock district, though it lies about 4 miles northwest of the town of Cave in Rock.

The deposits are mostly of two kinds, vein deposits and bedding-replacement deposits. The vein deposits are characteristic of the Rosiclare district, and the bedding-replacement deposits characterize the Cave in Rock district. In both kinds of deposits the chief gangue mineral is calcite. The vein deposits consist of veins of fluorspar extending along normal faults whose dips range from 45° to 90°. The veins vary in thickness, their maximum thickness being about 15 feet, and some of them extend as deep as the mines have been worked, which is more than 700 feet. The bedding-replacement deposits consist of nearly horizontal sheets roughly parallel to the bedding of the sedimentary rocks. All those that have been worked occur in the Cave in Rock district at and near the top of the Fredonia limestone. Detailed descriptions of the bedding-replacement deposits and of their geologic setting are given in part 1 of this report.

PROSPECTING METHODS

The methods of prospecting for additional fluorspar deposits have heretofore been more or less direct; the fluorspar has been detected by actual observation of the outcropping vein or of the residual gravel in the top soil in the vicinity of a deposit, or it has been sought by drilling and by digging test pits. This direct prospecting has always been conducted by private enterprise.

Related to the direct methods is that of geologic mapping, whereby the rocks cropping out on the surface have been identified and the principal faults located, thus permitting a choice of favorable locations for direct prospecting. Hardin County and a part of Pope County have been mapped geologically by the Illinois State Geological Survey and the Federal Geological Survey.[1]

In the search for more fluorspar there remains the possibility of applying some of the geophysical techniques currently employed in the search for petroleum and for certain ore minerals. Geophysical methods of prospecting may be divided into two classes: those by means of which the presence of the mineral sought is detected directly, and those which are useful indirectly because they detect structures commonly found in association with the minerals sought. Salt domes in the Gulf Coast region, for example, are directly detected by the use of seismographs and torsion balances; but in locating salt domes, oil and sulfur are commonly the minerals actually sought, since the salt domes frequently, though not invariably, are accompanied by oil and sulfur, which are therefore often found indirectly by prospecting for salt domes.

All geophysical prospecting consists in measuring physical properties (on top of the ground or in mines or drill holes) that are in some manner influenced by the presence or absence of the mineral or structures sought. This requires that the mineral or structure shall have some physical property that is susceptible of measurement. Such properties include density, elasticity, thermal conductivity, radioactivity, magnetic susceptibility, and electrical conductivity or

[1] Weller, Stuart, and others, The Geology of Hardin County Ill.: Illinois Geol. Survey Bull. 41, 1920.

resistivity. In respect to whatever property is to be used for its detection, the mineral or structure sought must contrast sharply with the surrounding rocks.

Fluorspar differs sharply from many minerals in being virtually nonmagnetic and nonradioactive and in having high electrical resistivity, but in these respects it closely resembles the calcite and the dense crystalline limestone with which it is most commonly associated. Its density, however, is 3.18, whereas that of calcite is only 2.7, and if the deposits of fluorspar were larger, they doubtless could be located by gravitational measurements, but their small size, together with the unevenness of the local topography, makes it impracticable to detect them by this means.

Direct methods of geophysical prospecting, then, do not appear to be applicable to fluorspar; but there remain the indirect methods, especially the detection of associated structures, of which the most common are faults. If the faults in the region can be accurately located, some of the fault fissures may be found to contain, or to lead up to, hitherto unknown fluorspar deposits.

Such a method is afforded by electrical-resistivity measurements, for there is a wide range of difference in electrical resistivity among the common sedimentary rocks. In rocks composed of the nonmetallic minerals, as Sundberg [2] has shown, this difference is due principally to the conductivity of the water filling the pores. When such rocks are free from water, they are almost perfect nonconductors of electricity, and if two rocks differing in porosity are both saturated with water, the more porous rock will be the better electrical conductor, provided the water in both is equally ionized. If two samples of similar rock having equal porosity are both saturated with water but the concentration of ionized salts is different in the two samples, the sample containing the lesser concentration of ions will be the more resistive.

It has been observed in the field,[3] and confirmed by laboratory tests, that water-saturated gravel deposits are more resistive than water-saturated sand, and the latter more resistive than clay.

As the county has already been mapped geologically, it might at first thought appear futile to devote more time and effort to locating faults. This would be true were it not for the fact that the geologic mapping is based largely on surface outcrops of rocks and that such outcrops are discontinuous and local. Not only are the rocks concealed in large part by residual soil, but the larger valleys contain extensive deposits of alluvium; over large parts of the county, moreover, there lies a blanket, ranging up to several feet in thickness, of the wind-

[2] Sundberg, Karl, Effect of impregnating water on electrical conductivity of soils and rocks: Am. Inst. Min. Met. Eng. Trans., Geophysical prospecting, pp. 367-391, 1932.

[3] Hubbert, M. K., Results of earth-resistivity survey on various geologic structures in Illinois: Am. Inst. Min. Met. Eng. Trans., vol. 110, pp. 9-39, 1934.

blown deposit known as loess. Underground mining operations, according to A. H. Cronk,[4] superintendent of the Rosiclare Lead and Fluorspar Mining Co., have disclosed two or three times as many faults as were detected by geologic mapping on the surface.

The evidence indicates, therefore, that there still are undiscovered faults in the area and that faults inferred from widely separated exposures will in many instances bear more precise location.

THE EARTH-RESISTIVITY METHOD

Where rocks have been faulted, formations of different lithology frequently occur on opposite sides of the fault. Where such differences occur at or near the surface of the ground, they should afford a means of locating the fault, provided a method can be found that is sensitive to lithological differences.

Since there are wide variations of porosity and water content as well as different degrees of ionization in the contained water in ordinary sedimentary rocks, rocks differing in composition and texture should differ in electrical resistivity. Differences of resistivity, measured in the field, may therefore be of service in locating geologic boundaries that cannot be traced by ordinary geologic methods.

TECHNIQUE OF EARTH-RESISTIVITY MEASUREMENT

In 1915 Wenner,[5] of the United States Bureau of Standards, described how the resistivity of the ground could be measured. The

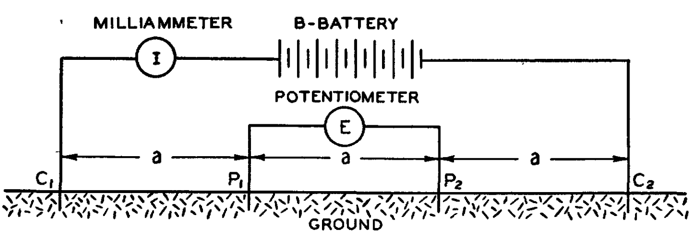


FIGURE 11.—Schematic diagram of the Wenner system for measuring earth resistivity.

method is essentially as follows: Four metal stakes, which are to serve as electrodes, are driven into the ground at equal intervals along a straight line. The arrangement is shown schematically in figure 11. Through the outer stakes C_1 and C_2 and the ground an electric current of strength I is made to flow. This causes a potential difference E to be set up between the inner pair of stakes, P_1 and P_2. The quantities measured are the current I, the potential difference E, and the electrode spacing a. Wenner showed that for the case in which the ground is

[4] Personal communication.

[5] Wenner, Frank, A method of measuring earth resistivity: Bur Standards Sci. Paper 258, July 15, 1914. Reprinted in Bur. Standards Bull., vol. 12, pp. 469-478, 1916.

flat, and homogeneous and isotropic with respect to electrical conductivity, the specific electrical resistivity ρ is given by the equation:

$$\rho=2\pi a \frac{E}{I}, \tag{1}$$

where ρ is in ohm-centimeters when a is in centimeters, E in volts, and I in amperes. (Were a measured in meters or feet, ρ would be in ohm-meters or ohm-feet, respectively).

VARIABLES IN THE WENNER METHOD

In actual field practice the condition that the surface be flat is usually approximated. The remaining two conditions for which the Wenner equation is valid—a ground homogeneous and isotropic to distances great as compared with a—are seldom realized. When under these circumstances the Wenner equation is applied to the measured values of a, E, and I, the value of ρ obtained no longer represents a true or even average resistivity of the ground, but an apparent resistivity whose manner of variation reflects departures of the ground from the ideal conditions postulated.

There are yet two more variables involved in the application of the Wenner method of resistivity measurements. These are the location of the station and the orientation or azimuth of the line of electrodes. The *location* of the station may conveniently be defined as the location of the center point between P_1 and P_2.

On a ground that is flat, homogeneous, and isotropic (such as a large and deep body of water) the value of ρ would be the same for all station locations and azimuths and for all values of a. If, on the contrary, the ground is inhomogeneous and anisotropic, the value of ρ differs in general for different station locations and azimuths and for different values of a. Thus the variation of the apparent resistivity ρ as a function of position, azimuth, and electrode spacing serves as an indicator of the inhomogeneity of the ground.

Three principal techniques of measurement are immediately suggested. They consist, respectively, in varying one of the three quantities—position, azimuth, and electrode spacing—while keeping the other two constant. The results of applying these techniques are briefly as follows:

I. Variation of azimuth:

This technique consists in taking a series of readings in different azimuths about a single station, with constant electrode spacing. The results are plotted graphically by means of polar coordinates with the station as the origin. For each azimuth a pair of equal and oppositely directed radius vectors whose lengths are proportional to the value of ρ for that azimuth are drawn. The ensemble of these vectors will, in general, give a dumbbell-shaped figure symmetrical about the station, with an axis of greatest and another of least apparent specific resistivity. (See fig. 16.) This procedure is useful in determining the strike of structural features.

When the resistivity is independent of the azimuth, the dumbbell-shaped figure will degenerate into a circle.

II. Variation of electrode spacing:

The second technique which suggests itself is to vary the electrode spacing while keeping the azimuth and the station position fixed. In this case the variation of ρ with the electrode spacing a reflects inhomogeneities with depth. It is useful where the ground is homogeneous in horizontal layers and permits the approximate determination of depths of distinctive layers.

III. Variation of station location:

The third technique consists in making measurements at successive stations while keeping the electrode spacing and azimuth constant. Measurements are made along a line of traverse and the value of ρ plotted as ordinates against distances as abscissas in a resistivity profile. The variations of resistivity in such a profile are due to lateral inhomogeneities of the ground.

In a resistivity profile, the effective depth to which the readings are influenced is controlled by the magnitude of the electrode spacing, a. Although, theoretically, inhomogeneities at any depth influence the readings, the variations in the apparent resistivity are due predominantly to inhomogeneities occurring at depths not greater than the electrode spacing a.

The azimuth remains an arbitrary element in resistivity traverses. Two principal cases suggest themselves—(1) when the line of electrodes is parallel to the line of traverse, (2) when the line of electrodes is perpendicular to the line of traverse. The latter arrangement has many theoretical advantages, but it renders field work slow and difficult; the former lends itself much more readily to rapid field work.

THE GISH-ROONEY APPARATUS

Gish and Rooney [6] were among the first to build apparatus by which to apply Wenner's method to measurements of earth resistivity. They developed an apparatus that differed somewhat from the one suggested by Wenner but that employed the same basic theory.

The Gish-Rooney apparatus, a form of which was employed in the work in Hardin County, consists of a radio B-battery to supply the current, a milliammeter to measure the current I, a potentiometer to measure the voltage E, and a double commutator. The purpose of the commutator is to alternate the current entering the ground and then

[6] Gish, O. H., and Rooney, W. J., Measurement of resistivity of large masses of undisturbed earth: Terrestrial magnetism and atmospheric electricity, vol. 30, pp. 161–188, 1925.

to rectify the alternating potential difference E occurring across the potential stakes. Direct-current instruments may thus be used while an alternating current is maintained in the ground. An alternating current is used because it eliminates the effect of stray ground currents and balances out effects due to the large potential differences that occur spontaneously between the potential stakes because of electrolytic reaction with the ground.

The use of a potentiometer for measuring E has the additional advantage that it allows no current to flow in the potential circuit while readings are being made, so that the contact resistances of the potential stakes do not appreciably affect the readings.

The commutators used by Gish and Rooney gave an alternating current frequency of about 25 cycles per second. The frequency produced by the present apparatus was about 10 to 12 cycles per second.

It has been found that, in spite of the commutation, enough stray voltage frequently gets through to the potentiometer to make its readings extremely unsteady, and hence inaccurate. This unsteadiness can be totally eliminated by placing a condenser in series between the commutator and the potentiometer. A condenser of 25 microfarads was used in the present work, but subsequent tests have shown that a very much smaller condenser, possibly as small as 1 microfarad, would do equally well. The optional use of a condenser was suggested by Gish and Rooney.

FIELD METHODS USED IN HARDIN COUNTY

The method employed in Hardin County was that of Wenner, described above, and the apparatus used was one of the Gish and Rooney type, copied from a design by F. C. Farnham of the Missouri Bureau of Geology and Mines.

The measurements were made along traverses in which the location of the station was varied but the azimuth and electrode spacing were kept constant. The line of electrodes was kept parallel to the line of traverse. The electrode spacing a was 100 feet except on two traverses on which it was 200 feet. Readings were taken at intervals equal to the electrode spacing—100 feet in all but the two traverses mentioned above.

In the Rosiclare area, most of the traverses ran east and west, transverse to the strike of the dominant system of faults (N. 30° E.). In the Cave in Rock area, two sets of mutually perpendicular traverses, extending in general northwest and northeast, were run. These were respectively about parallel and perpendicular to the Peters Creek fault zone, the dominant structure of that area.

FIELD OPERATIONS OF RESISTIVITY PARTY

The crew of the resistivity party consisted of an instrument man, a front lineman, and a rear lineman. Each of these men followed a definite routine. The instrument man took a reading, which he either recorded himself or called out to the rear lineman, serving as note taker. The rear lineman then pulled up the last stake and brought it forward to the front lineman. The instrument man disconnected the two front lines from the instrument and moved forward a distance of one electrode interval, dragging the rear lines. The front lineman dragged forward the two front lines, set the front stake, and connected the lines. The instrument man reconnected the front lines; the rear lineman connected the two rear lines to the stakes and another reading was taken. This cycle was repeated until the traverse was covered.

The speed at which traversing can be done depends upon the nature of the country to be crossed. Along a road it is possible to make 100 stations, at intervals of 100 feet, in a day. In wooded or brushy country the rate is very much slower, 50 stations, or a mile of traverse, being a good day's work. If the lines of traverse are to be kept straight in wooded or brushy country, especially in country infested with blackberry brambles, it is almost necessary for the front lineman to be equipped with some form of machete (a corn knife does very well) and time can be saved by providing machetes for the instrument man and the rear lineman also, in order that all hands may join in clearing the line ahead when particularly brushy stretches are encountered.

METHOD OF CONTROL

The ordinary Geological Survey topographic map, on the relatively small scale of about one inch to the mile, is too generalized and not sufficiently accurate in small details to be of service, except as a general guide map, in work of this sort. The following method of control was therefore adopted:

The traverses, except when a winding road was followed, were run as nearly as possible in straight lines controlled by a Brunton compass. The leads to the ground electrodes were marked and used as tapes for measuring distances along the traverse, which could thus be determined within ± 1 percent. At the beginning and end of each traverse, and wherever a traverse crossed a main road, a flag was set that was marked with the station number for that point—a flag set 30 feet ahead of station 28, for example, would be marked station 28.3.

In addition to the nearly straight cross-country traverses, plane-table traverses were run along the principal roads, on which the positions of the flags, fences, and principal land lines were plotted. The traverses run in the Cave in Rock area were located on a large-scale topographic map, which was made primarily as a base for the geologic work described in part 1.

Between the points on the resistivity traverse that were located by plane-table, control was effected by a graphic system of note taking. In the left-hand margin of the notebook page a vertical line was drawn to represent the line of traverse. A point on this line represented graphically the location of the station, and the locations of houses, fences, roads, creeks, ridge crests, and various geologic features with reference to the station were sketched in.

When the readings were computed and a resistivity profile plotted, the resulting map of the traverse, properly oriented, was plotted to the same scale below the graph of the profile (pls. 21 and 23). With this map in hand it is possible, by following the line of traverse, to locate any station within a few feet by measurement from some nearby feature whose position has been recorded.

RELATION BETWEEN APPARENT RESISTIVITY AND GEOLOGIC STRUCTURE

Since any subsurface inhomogeneity, within the depth range of the instrument, of the rocks along the line of traverse may cause variation in the observed apparent resistivity, it is well before attempting to interpret the actual resistivity curves obtained in the field to consider, at least qualitatively, the variations that are likely to be caused by the various geologic conditions that are most likely to be encountered. Faults are what is chiefly looked for, but the other features by which resistivity is affected must be taken account of in order that their influence may not be wrongly ascribed to faults.

RESISTIVITY VARIATION DUE TO FAULTS

The present discussion concerns only the faults that have dips of more than 45°, for no faults of lower dip occur in Hardin County. The resistive properties along these steep faults may be divided into three more or less distinct parts—the resistivity of the two blocks on the one side and on the other side of the fault zone and the resistivity of the fault zone itself.

An idealized condition is shown in figure 12, where the resistivity of the block to the left is ρ_1, that of the fault zone ρ_2, and that of the block to the right ρ_3. Various combinations of ρ_1, ρ_2, and ρ_3 are possible. For example, we may have all three unequal:

$$\rho_1 \neq \rho_2 \neq \rho_3,$$

or we may have what amounts only to two blocks with a sharp bounding interface, when:

$$\rho_1 \neq \rho_2 = \rho_3,$$

or the two fault blocks may be of equal resistivity while the fault plane itself is either more resistive or more conductive than the blocks:

$$\rho_1 = \rho_3 \neq \rho_2.$$

In nature, a fault zone rarely consists, as these equations assume, of a simple sheet whose resistivity is uniform; it may consist of laminae that differ greatly in resistivity. This might well be the case for a fault containing both resistive vein material, such as fluorspar or calcite,

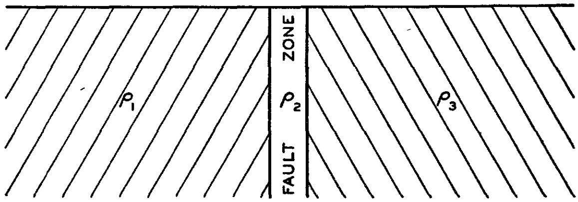


FIGURE 12.—Three resistivity blocks associated with a vertical fault.

and highly conductive fault gouge. Such a fault zone would be highly anisotropic, showing high resistivity to a transverse flow of current but low resistivity to a longitudinal flow. There is field evidence that zones of this type are not uncommon.

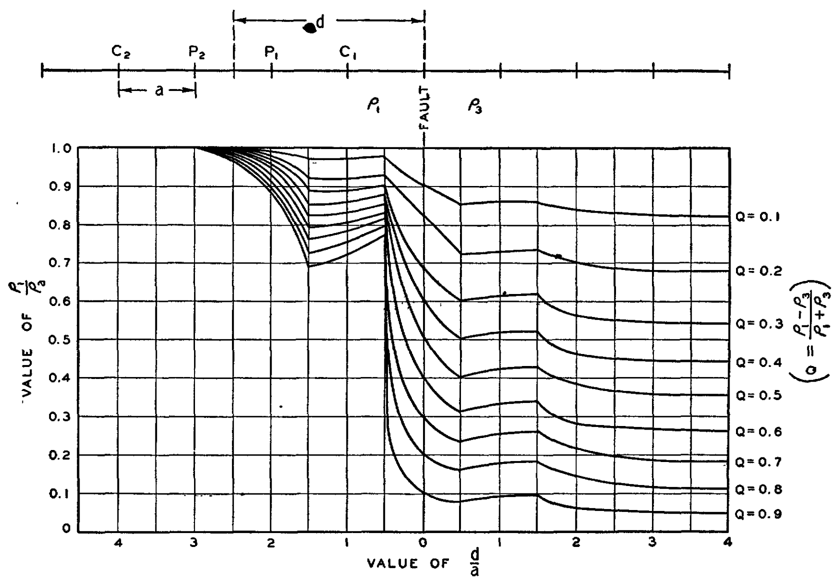


FIGURE 13.—Variation of apparent resistivity across a vertical fault. After Tagg.

Some enlightening theoretical and experimental work pertaining to these various combinations and permutations has been done by several men.

Tagg [7] (fig. 13) has computed the resistivity curves for the case of a simple fault where

$$\rho_1 \neq \rho_2 = \rho_3$$

[7] Tagg, G. F., The earth resistivity method of geophysical prospecting: Mining Mag., vol. 43, pp. 150-158, Sept. 1930.

with the line of electrodes at right angles to the strike of the fault plane. The readings are indicated continuously rather than at discrete intervals, and for all ratios of ρ_1/ρ_2. It is worth note that the curve is not smooth; it becomes angular wherever an electrode crosses the fault plane.

Howell [8] (fig. 14) has computed similar curves for the cases where $\rho_1=\rho_3$ and the fault zone is either infinitely conductive or infinitely

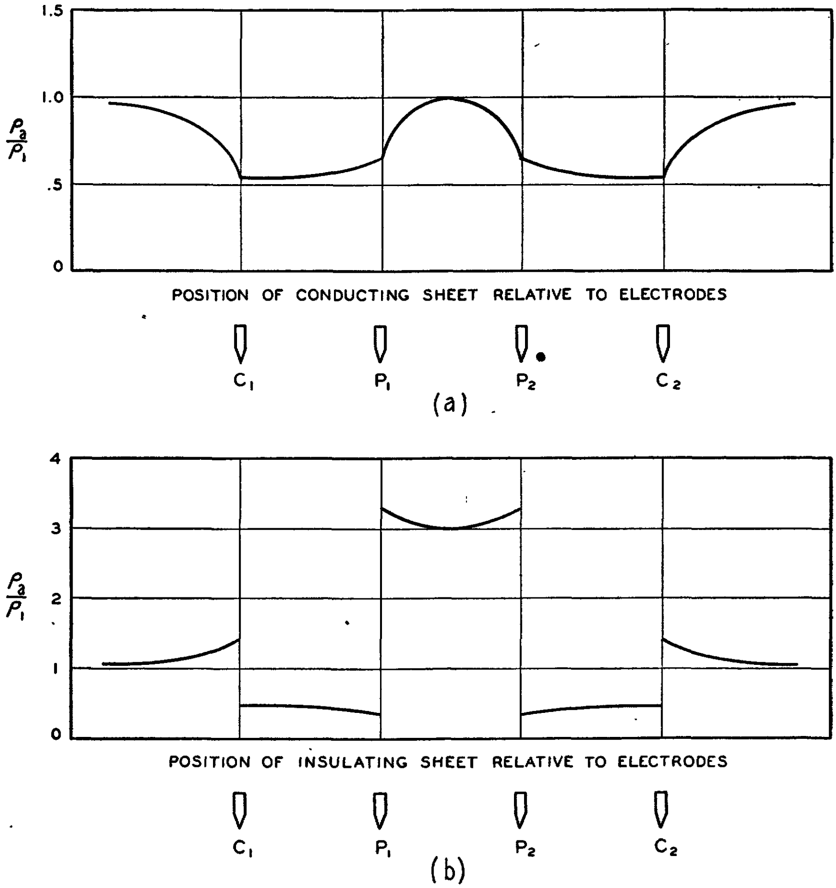


FIGURE 14.—Variation of the apparent resistivity across (*a*) a vertical highly conductive sheet and (*b*) across an insulating sheet. After Howell.

resistive. In these cases also the curves are angular at the points where an electrode crosses the fault. When the resistance is infinite, the curves are even discontinuous at these points. The outstanding characteristic of the curves, however, is their W shape. When the fault zone is infinitely resistive, the central peak of the W is higher

[8] Howell, L. G., Discussion of paper by M. King Hubbert: Am. Ist. Min.-Met. Eng. Trans., vol. 110, Geophysical prospecting, pp. 34-37, 1934.

than the resistivity of the surrounding region; when it is infinitely conductive, this peak is equal to the resistivity of the two sides.

Others [9] have made tank experiments on conductive and resistive sheets. For thin sheets a W shape, similar to that given by Howell, is characteristic. A thick conductive sheet, however, produces a resistivity trough. As the sheet is made thinner, an arch begins to form in the bottom of the trough, and as the thickness of the sheet approaches zero this arch rises to the level of the resistivity of the surrounding medium. If the conductive sheet is then replaced by a resistive one, the peak becomes still higher, and it continues to rise as the resistive sheet is thickened.

The anisotropic condition caused by alternation of conductive and resistive sheets was inadvertently produced by the author [10] (fig. 15).

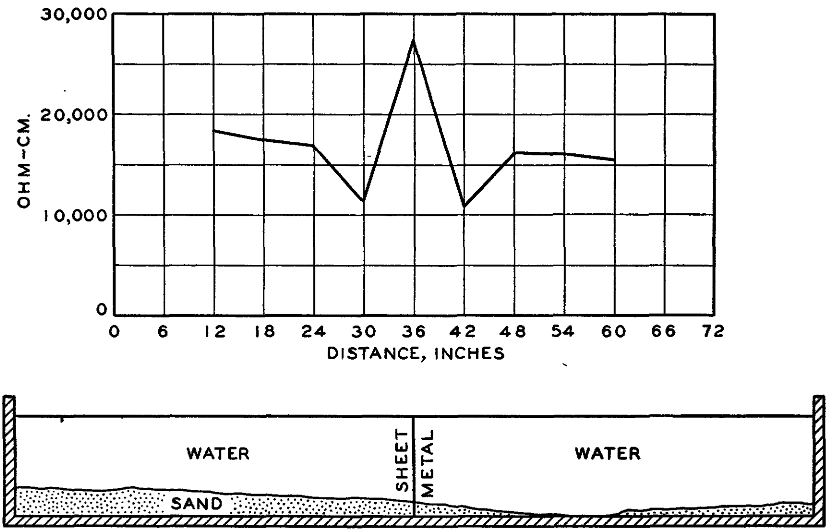


FIGURE 15.—Apparent resistivity in a traverse across a vertical sheet of metal with a slightly oily surface, immersed in water.

A piece of sheet metal with a greasy surface was immersed in a tank of water and a profile transverse to the sheet was taken (fig. 15). From what has been said about it is evident that the high-peaked W indicates a resistive sheet. Next, the station was taken directly above the sheet and readings made in different azimuths (fig. 16). The radial vectors representing the resistivity in various directions, when plotted in polar coordinates, generate a symmetrical dumbbell-shaped figure, which shows a resistivity higher than that of the water in a direction normal to the sheet and a resistivity lower than that of the

[9] Zuschlag, Theodore, Discussion of paper by M. King Hubbert: Am. Inst. Min. Met. Eng. Trans., vol. 110, Geophysical prospecting, p. 30, 1934.

[10] Hubbert, M. K., Results of resisitivity survey on various geologic structures in Illinois: Am. Inst. Min. Met. Eng. Trans., vol. 110, Geophysical prospecting, figs. 2, 3, 1934. See also discussion by L. G. Howell, op. cit., pp. 34-37.

water in the direction parallel to the sheet. This indicates that the sheet is more resistive than the water to a transverse current, and more conductive than the water to a longitudinal current. Such a figure as this would give the strike of the sheet were it not already known.

In the limiting case where $\rho_1=\rho_2=\rho_3$ there obviously will be no variation but this case would virtually never occur in nature.

The foregoing discussion provides us with a clue to what may be expected when a real fault is crossed perpendicularly by a resistivity traverse. It is not to be forgotten that in actual field work readings are not taken continuously, but at discrete points separated by the electrode interval a. The readings obtained should be points on a curve resulting from some combination of the separate effects described

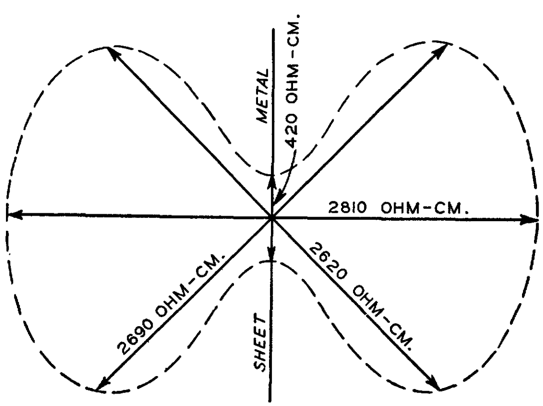


FIGURE 16.—Variation of apparent resistivity as a function of azimuth with the station directly above the metal sheet of figure 15.

above. If the fault zone is narrow as compared with the electrode interval, its effect, if it has any, should be visible in the readings for not less than three consecutive stations, since the line of electrodes spans the fault of three consecutive stations. The resistivity curve may merely oscillate, or it may level off to a higher resistivity on one side and a lower resistivity on the other, depending upon the resistivities of the blocks on the opposite sides of the fault.

If the width of the fault zone is w, the resistivity of the zone should affect the readings on a traverse perpendicular to the zone for a distance of not less than $w+3a$. On a traverse oblique to the fault zone, the effect of its resistivity will persist for a longer distance.

EFFECTS DUE TO INTERRELATIONS BETWEEN TOPOGRAPHY AND STRATA

Different stratified rocks, such as sandstone, shale, and limestone, differ in resistivity, so that contacts between them would be marked by flexures in transverse resistivity profiles. Only a small proportion of such contacts are fault contacts. When the contact between two sedimentary rocks reaches the surface, it is most commonly because the strata are folded and tilted, or because the surface is uneven, or because the two conditions co-exist. In one class of ideally simple

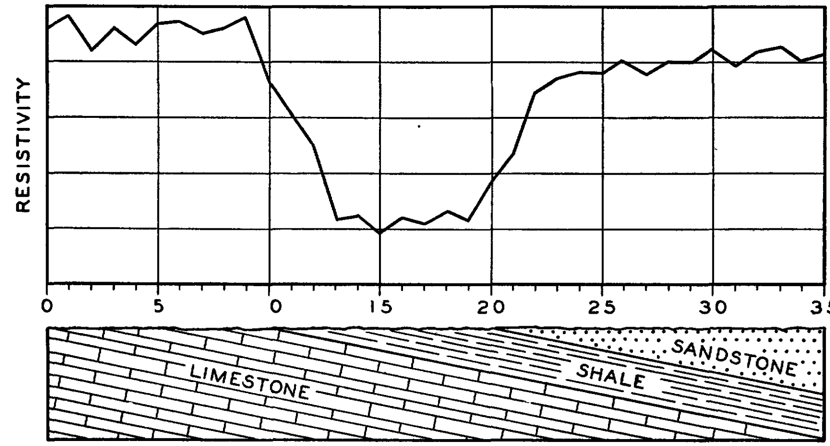


FIGURE 17.—Variation of apparent resistivity along a traverse over a level surface normal to strike of dipping strata.

cases, tilted and folded but unfaulted strata are truncated by a plane topographic surface; in other cases, more often approached in nature, horizontal strata are dissected by an uneven eroded surface. The most

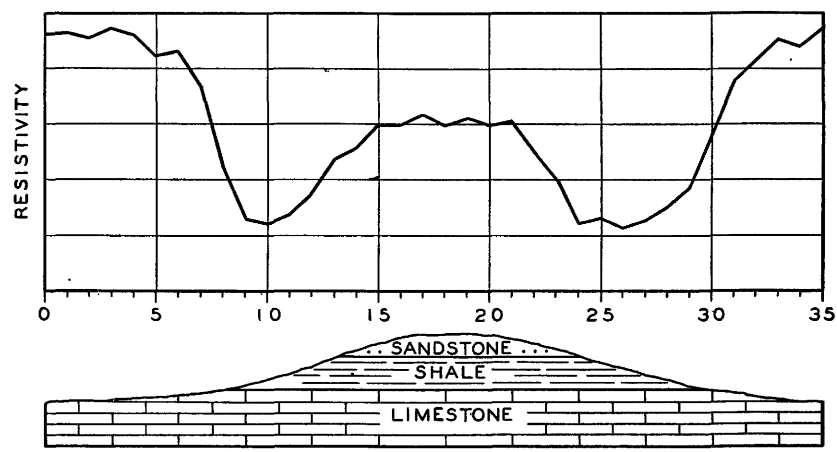


FIGURE 18.—Variation of apparent resistivity produced by successive horizontal strata along a traverse across a ridge.

general case, however, and the commonest, is that of folded strata cut by an uneven eroded surface.

In those parts of Hardin County in which the present work has been done, the rocks are but slightly flexed. The dips of the strata in the individual fault blocks vary from zero up to a maximum of 10° or 15°.

The cases that concern us, therefore, are those involving strata with gentle homoclinal dips; and these strata crop out on a topography that is not rugged on the whole but that includes some steep slopes as well

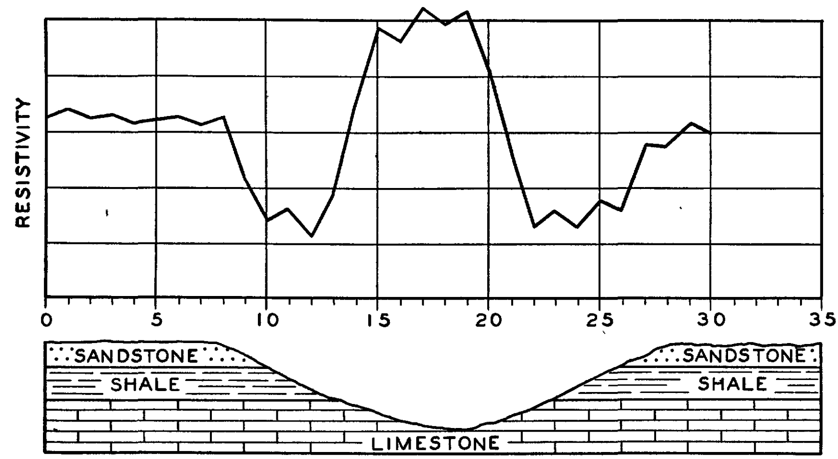


FIGURE 19.—Variation of apparent resistivity produced by successive horizontal strata along a traverse across a valley.

as fairly extensive areas of very low relief. Some effects of structures and topographic features resembling those found in this region are illustrated in figures 17–20. Figure 17 gives an idea of the type of

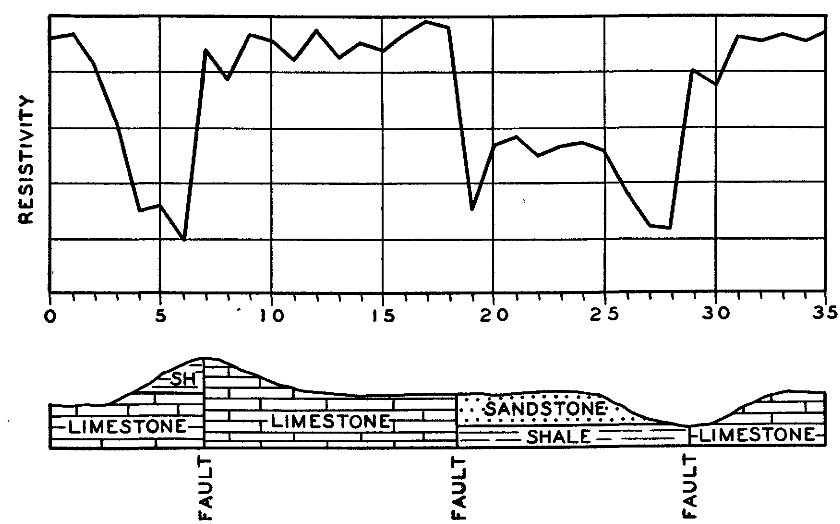


FIGURE 20.—Variation of apparent resistivity along a traverse across horizontal strata with faulting and with topographic relief.

resistivity variation that may be expected from a traverse across the strike of uniformly dipping strata. The sharpness of the transition will vary with the steepness of the dip, being gradual for gentle dips and more abrupt for steep dips. The variations are asymmetrical. Figures 18 and 19 depict traverses across a valley and a ridge respectively, both underlain by horizontal strata. The resistivity curve across either a valley or a ridge may itself be either troughlike or ridgelike, depending upon whether the more resistive rocks crop out on the sides or in the middle. But any resistivity curve crossing a symmetrical valley or ridge underlain by horizontal unfaulted strata should be more or less symmetrical about the axis of the valley or ridge, and any marked asymmetry in a resistivity curve that cannot be accounted for either by dipping strata or by topography is quite probably due to the presence of a fault (fig. 20).

EFFECTS DUE TO WEATHERING AND TO ALLUVIUM

Other effects are due to the fact that the surface of the ground is blanketed over large areas either by residual soil or alluvium. These

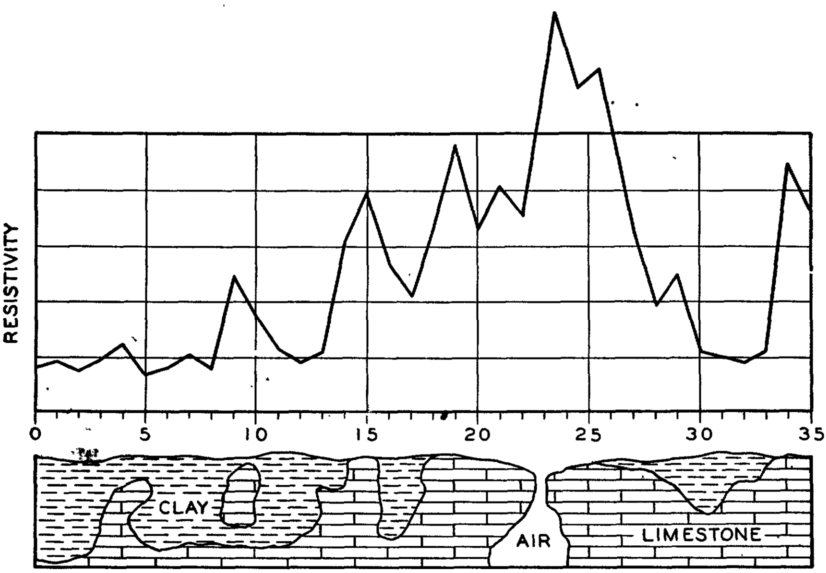


FIGURE 21.—Erratic variation of resistivity across karst topography.

surficial deposits, with the exception of loose dry sand, are almost always highly conductive, and where their thickness is large in comparison with the electrode interval used they may lead to false interpretation of the profiles.

The Fredonia limestone in Hardin County is particularly hazardous in this respect. Upon weathering, its lime carbonate is dissolved, and there remains a stiff, red clay, which is highly conductive, whereas the limestone itself is among the most resistive rocks in the area. The limestone does not dissolve uniformly; its surface, beneath the residual clay, is marked with crevices and deep pockets of various depths, with pinnacles of undissolved limestone between. A further complication is produced by the fact that the Fredonia forms sinkholes and caverns, which may contain open air spaces of infinite resistivity (fig. 21). Resistivity curves crossing such a limestone may be expected to oscillate erratically between the widest extremes, and so in fact they do.

FAULT INTERPRETATIONS AS A FUNCTION OF DISTANCE BETWEEN TRAVERSES

Let us suppose that a series of parallel resistivity traverses, spaced at a uniform distance *d*, have been run across an area transverse to the strike of the dominant faults. Assuming that all the faults so crossed show up on the resistivity curves (which is improbable) we have then the problem of correlating the faults found on one traverse with those on the next.

The complexity and difficulty of this problem are much increased if the faults are numerous, irregular in strike, and short. If, for example, there is only one fault in the area and this fault shows up on three or more adjacent profiles, its location is uniquely determined. If, on the contrary, the rocks are broken into polygonal blocks bounded on all sides by faults, and if many of these faults are so short that they do not extend from one traverse to the next, there are an infinite number of possible interpretations of the resistivity data, all but one of which are wrong. In other words, the probability of finding one, and only one, fault pattern that completely satisfies all the resistivity data is zero.

When, therefore, an area of complicated block faulting exists and the distances between adjacent traverses are too large to enable one to determine the pattern, complete solution of the problem would require closer spacing of the traverses. A 100-foot spacing of the lines forming the grid work is not at all too close for the precise locating of features for mining purposes, particularly for the purpose of controlling exploration by drilling or other methods. Stations on a regular grid can be supplemented by stations taken on lines of different azimuth drawn through single points, in order to determine the strike; and depth tests may be made where needed.

The uncertainty of correlation between traverses that are too widely spaced in a hypothetical area of complex fault pattern is shown in figure 22. Figure 22, *a*, shows what is assumed to be the actual fault pattern. It is assumed, also, that there are only two kinds of rock at the surface, one of high and the other of low resistivity. A fault will then be indicated on a resistivity profile across the area only if that profile crosses the fault where it brings rocks of high and low resistivity together at or near the surface. Two traverses across the area are shown. In figure 22, *b* and *c*, the results are shown of two

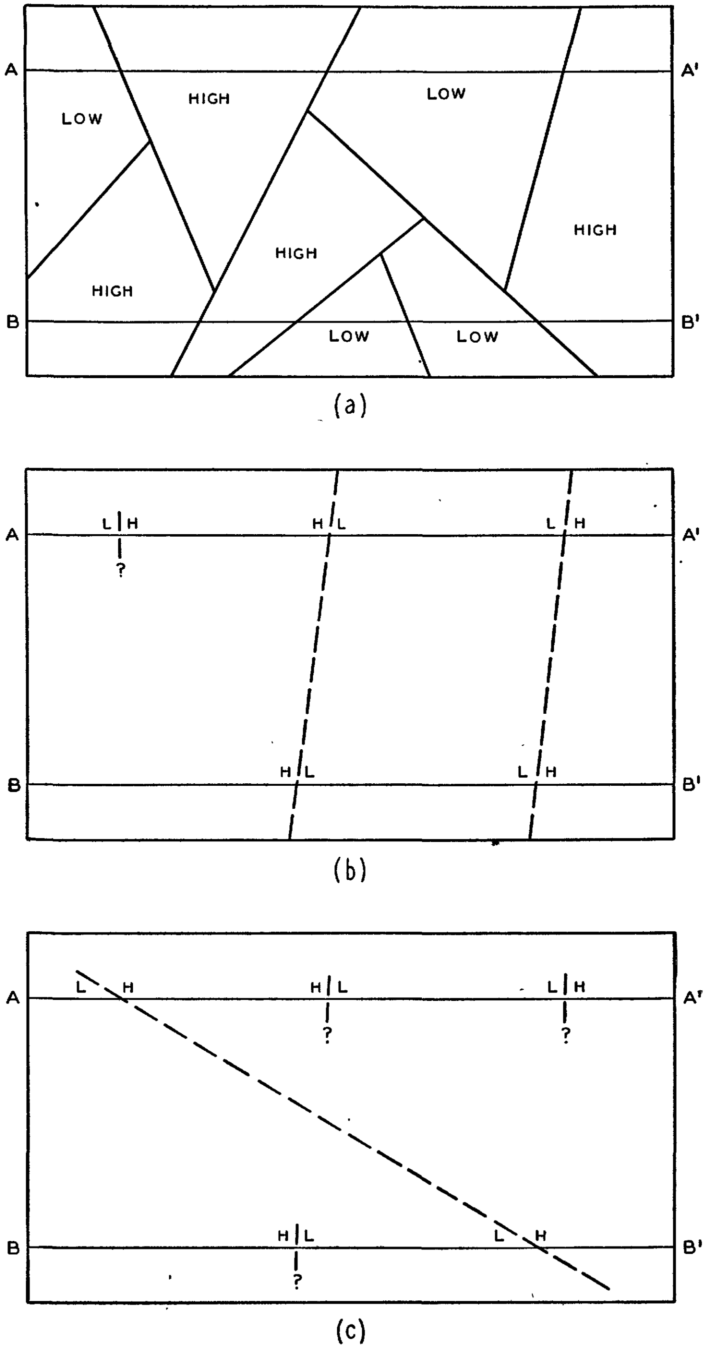


FIGURE 22.—Difficulty of correlating the faults shown by resistivity profiles A–A' and B–B': (*a*) The true fault pattern; (*b*) and (*c*) attempts to correlate the resistivity anomalies.

attempts to correlate the resistivity data on these and to construct the fault pattern from them; both results, though consistent with the data, fail to give the fault pattern of figure 22, *a*, which by hypothesis is the correct one.

EXTENT AND SCOPE OF THE PRESENT WORK

Preliminary test traverses, together with considerations such as the foregoing, early made it evident that isolated or too widely spaced traverses in Hardin County would be comparatively useless. Work in minute detail, on the other hand, such as mining companies might find it profitable to do on their own properties, were much beyond the facilities of the present undertaking; a season's work on that scale would probably have covered less than one square mile. Hardin County as a whole, on the other hand, was too large a unit to be covered in the time available. A compromise plan was therefore adopted, whereby the work was confined to two of the more likely fluorspar-bearing areas, across which traverses were run as close together as time would allow. The closest spacing achieved was about one-eighth of a mile. Although this spacing was adequate for locating the longer faults, it was not close enough for certain areas where the fault pattern appears to be complex; in a number of cases, correlation of major faults across several traverses seems certain, but any attempted correlation in the more complicated areas would probably be wrong. On the whole, the resistivity work that has been done must be regarded as reconnaissance. Enough has been done, however, to indicate a number of things about each of the districts that were studied, and to give a fair idea of what may be expected from further work of this kind.

The two districts selected for study are the Rosiclare and the Cave in Rock. The Rosiclare district is bounded on the east by a north-south line about one mile east of the town of Rosiclare, on the north by the center line of T. 12 S., on the west by Big Grand Pierre Creek, and on the south by the Ohio River. The Cave in Rock district is contained within secs. 27, 33, and 34, T. 11 S., R., 9 E., and secs. 3, 4, and 5, T. 12 S., R. 9 E.

In the summer of 1931 A. H. Bell, of the State Geological Survey, and the writer made an inspection trip to Hardin County for the purpose of ascertaining what, if any, kind of geophysical method could be applied. During this time Mr. Robert Weaver of the Franklin Fluorspar Co. was kind enough to demonstrate to us a set of Gish-Rooney apparatus, which he had obtained from the Colorado School of Mines. Later in the same summer P. S. McClure and the writer returned to Hardin County with a Megger ground tester, with which tests were made on selected known faults in various parts of the county. The results as a whole seemed positive enough to warrant further work.

In the summer of 1932, therefore, the writer, with Robert P. Stevens and Ben Richards as field assistants, returned to Hardin County with a set of Gish-Rooney apparatus, and did six weeks' work in the Rosiclare district. Profiles were constructed from the data that were obtained, and possible faults were indicated. These profiles were then taken into the field by J. Marvin Weller, who checked the indicated faults by geologic evidence. Many of the inferences from the preliminary traverses were thus confirmed[11] and it was accordingly decided that more detailed work was justified.

In 1934 the work was resumed as a Public Works Administration project, under the direction of the Federal Geological Survey and with the cooperative sponsorship of the Illinois State Geological Survey. This time a larger party, comprising both a geologic and a resistivity crew was available. Its members were: L. W. Currier, geologist; M. King Hubbert, geophysicist; C. G. Dickinson, geologist and plane-table man; D. S. Hughes, physicist; O. E. Wagner, Jr., stratigrapher; and R. P. Stevens, lineman and computer.

Six weeks were allotted to Illinois and six to Kentucky. During this season resistivity work was confined to the Rosiclare district except for a few test lines in the Cave in Rock district; geologic work was carried on in both districts.

The task was concluded in 1935, still under the joint auspices of the Federal Geological Survey and the Illinois State Geological Survey. The party was the same as that of the preceding summer except that Hughes and Stevens were replaced by Gilbert H. Cady, Jr., and A. L. Skrobisch. During this season both geologic and resistivity work were confined to the Cave in Rock district, except for a few final traverses run in the Rosiclare district.

ACKNOWLEDGMENTS

Acknowledgments are due to many of those engaged in the fluorspar-mining industry of Hardin County for faithful cooperation, without which much of the present work would have been impossible. Among the many to whom we are especially indebted are: A. H. Cronk, Superintendent of Rosiclare Lead and Fluorspar Mining Co.; E. C. Reeder, late Superintendent of Hill Side Fluorspar Mines Co.; J. W. H. Blee, Superintendent of Benzon Fluorspar Co.; Martin Schwerin, President of Victory Fluorspar Mining Co.; Miles Haman, Engineer, Crystal Fluorspar Mining Co.; Robert Weaver, Engineer, Franklin Fluorspar Mining Co., and many other members of the staff; Arthur J. Lay, Crystal Fluorspar Mining Co.; and Dodson Gibson, Engineer, Crystal Fluorspar Mining Co.

[11] Hubbert, M. K., and Weller, J. M., Location of faults in Hardin County by the earth-resistivity method: Am. Inst. Min. Met. Eng. Trans., vol. 110, pp. 40–48, 1934.

RESISTIVITY PROFILES OF THE ROSICLARE DISTRICT

The Rosiclare district as defined for the purposes of this report extends about 1 mile east and about 3 miles north of the town of Rosiclare; it is bounded on the west by Big Grand Pierre Creek and south by the Ohio River. As will be seen by reference to plate 20, this area was by no means fully covered by resistivity traverses, but the above boundaries enclose all the traverses run in this part of Hardin and Pope Counties. Altogether 224,000 feet of traverses, with readings taken at every 100 feet, were run in the Rosiclare district. This work represents 2,240 separate measurements of resistivity.

The locations of the various traverses in the Rosiclare district are shown in plate 20, and the profiles are plotted in plate 21. In general the traverses largely followed straight east-west lines, though some of them (notably profiles 3, 10, and 16) were run along roads that extend only approximately east and west.

Although a few of the profiles extended entirely across the district, most of them were confined to one or the other of two parts of it, one to the east and the other to the west of the township line between R. 7 E. and R. 8 E. The work in the eastern area was mainly focused upon the fault system associated with the active mining district around Rosiclare; that in the western area was mainly devoted to a detailed study of the alluvium-filled valley of Wallace Branch.

Between these two areas is a strip roughly a mile wide, extending along the north-south township line, in which little work was done, because the country rock is mostly Caseyville conglomerate in the southern part of the strip and Fredonia limestone in the northern part, and faults in either of these formations are not likely to be revealed by resistivity profiles. Similar considerations apply to other regions left blank on the map. Because of the limited time, the work was confined to the more promising parts of the district.

In plate 21, also, an endeavor was made to correlate, between successive resistivity profiles, the anomalies or irregularities that appear to indicate intersections with faults. Where a similar anomaly appears on many successive profiles along a nearly straight or gently curving line, there can be little doubt that it represents a single fault. In some cases, however, correlation from one profile to another is highly conjectural, and there may even be doubt as to whether or not certain individual anomalies are due to faults. In the vicinity of Stone school, for example, the anomalies can be correlated in many different ways, and here a study of the areal geology has revealed a complex pattern of faults.

The geophysical data are not complete enough to justify revision of the areal geology map of the Rosiclare district. Although areal mapping was done in this district, the results did not differ enough from the earlier work of Stuart Weller to justify a revision of his maps. It is true that mining operations have disclosed more faults than were detected by geologic mapping. Resistivity methods, however, can at best only determine the location of faults; they cannot of themselves identify the wall rocks. They could not, therefore, fill in all the missing details of a map made by ordinary methods, even if they succeeded in locating every fault in the mapped area; the identity of the formations flanking a concealed fault located by geophysical methods would have to be guessed at. Fortunately, however, it is the location of the faults, rather than the identity of the bordering formations, that is of primary importance in prospecting for vein deposits of fluorspar. It therefore seems worth while to try to locate faults that had not been located by geologic mapping.

Since the data in many cases can be variously interpreted, many particular interpretations may be wrong. This report therefore presents the original resistivity data, in order that they may be reinterpreted, when it seems desirable, by or on behalf of persons who are seeking fluorspar. The interpretations are subjective, representing the author's opinions; the data are objective and based on instrumental observation.

DISCUSSION AND INTERPRETATION

EASTERN AREA

The traverses made in the eastern area of the Rosiclare district are plotted, from south to north, on profiles 1 to 16, plate 21. All except profiles 1 and 2 form a sequence of approximately east-west profiles with station intervals of 100 feet and electrode spacing of 100 feet.

Profiles 1 and 2 were taken with stations at 200-foot intervals and electrode spacing of 200 feet. They lie apart from the others and are discussed separately on pages 106 and 107.

Profile 3

The noteworthy resistivity anomalies in profile 3, reading from west to east, are as follows: A small rise between stations 77 and 68 coincides with a topographic rise that is flanked on either side by alluvium. The higher resistivity is probably due to the nearness of bedrock to the surface.

Between stations 55 and 51 there is an abrupt rise in resistivity, with the higher level approximately four times the lower. Station 53 is at the crest of a small ridge. If the rocks were the same on both sides of the ridge, the resistivity anomaly should be symmetrical with respect to the ridge crest, but in fact the anomaly is highly asymmetrical and suggests a fault near station 53.5.

The high-resistivity block encountered at 53.5 ends near station 40, on the crest of another small ridge. This fact is interpreted as being due to a fault at or near station 40.

From stations 33 to 29 there is an abrupt rise of resistivity, east of which the curve remains high to station 20, but from there to station 18 it drops sharply. This region of high resistivity coincides in general with a rather broad ridge, of which the top consists of Hardinsburg sandstone and the slopes of Golconda limestone. These two changes in resistivity thus appear to be due to the transition from the Golconda to the Hardinsburg and back again in ascending and descending the ridge.

From stations 7 to 4 the curve shows some minor oscillations and then rises abruptly. Station 5, near which the curve rises to a high peak, is at a prospect shaft on the Blue Diggings fault.

Profile 4

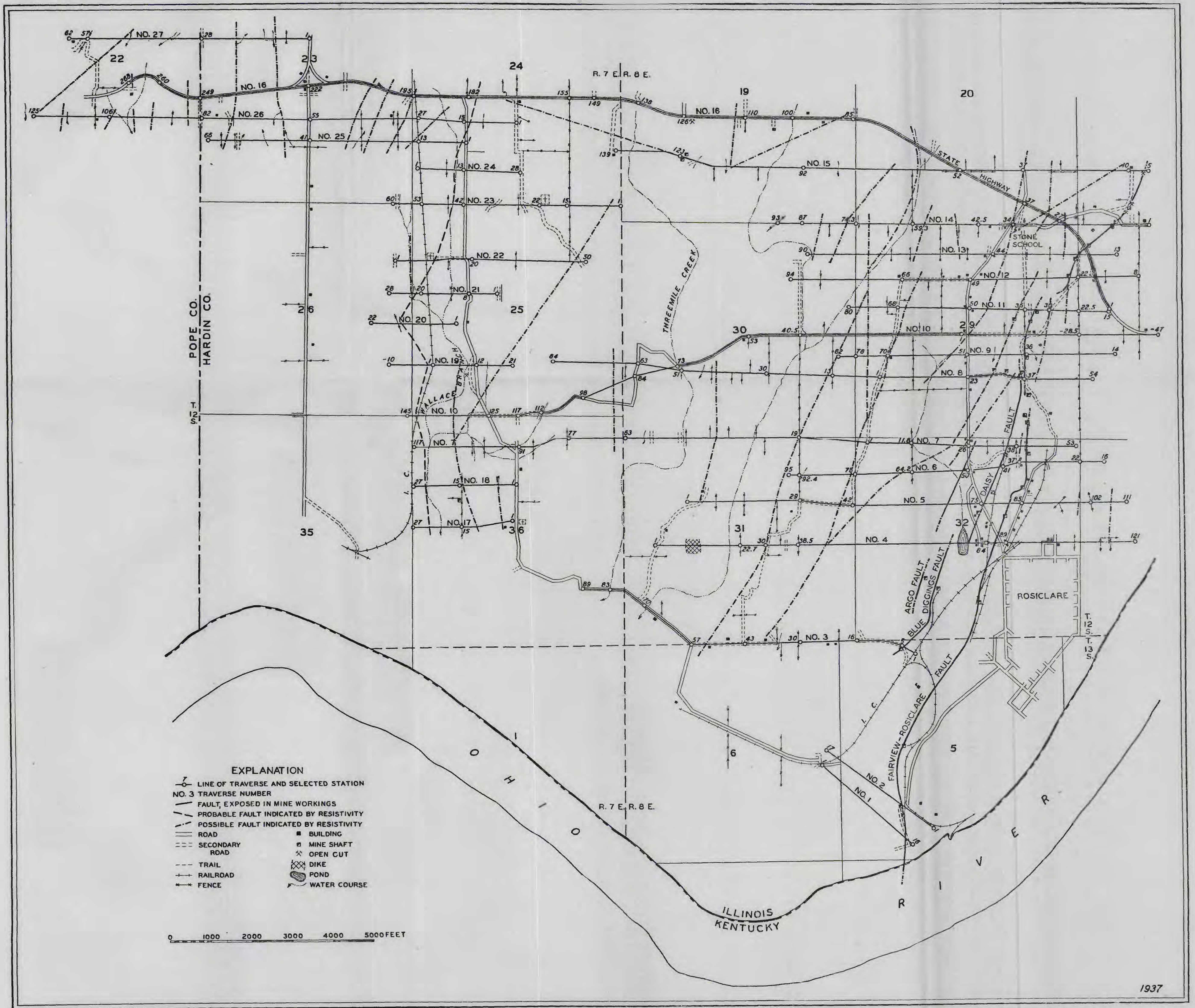
Between stations 8 and 9 on profile 4 there is a sharp rise that coincides with the western border of a dike or volcanic neck. How far the dike extends in the line of traverse is somewhat uncertain, but it is exposed at station 12, and the decline of the resistivity curve at station 15 suggests that it may not extend any farther east.

The low resistivity from stations 17 to 28 represents an alluvium-filled valley. Between stations 30 and 31 the curve rises somewhat sharply. This rise might be regarded as merely marking the boundary of the alluvium, but its abruptness and sharpness, and its correlation with similar features in the adjacent profiles, indicate that it has some other cause. Correlation across several profiles indicates a fault at about station 30, apparently the same as the one at station 53.5 on profile 3.

Station 41.5 is at the crest of a ridge of Palestine sandstone, and at station 44 there is an outcrop of limestone. As the ridge crest is approached from the west the resistivity profile descends rather sharply—an effect that might be due either to faulting or to the fact that the sandstone dips westward—and as the crest is passed the influence of the Menard limestone and shale becomes evident.

Geologic data show that there is a fault between stations 40 and 47, for the sandstone on the next ridge to the east is the Hardinsburg sandstone, and at station 45, moreover, there is a small valley which, as shown by the areal map, has Golconda limestone on the east side and Menard limestone on the west. A fault is accordingly placed at station 45.

Near station 49 the curve rises again, apparently marking the transition from the Golconda limestone to the Hardinsburg sandstone in normal stratigraphic sequence.



MAP OF THE ROSICLARE DISTRICT, HARDIN COUNTY, ILL., SHOWING LOCATION OF EARTH-RESISTIVITY TRAVERSES AND FAULTS.

At station 67 the curve descends abruptly, the descent coinciding with an eastward-facing scarp of Hardinsburg sandstone, probably at its eastern contact with the Golconda limestone.

At station 74 the curve rises, and at station 75 there is a prospect pit on what is evidently the northward extension of the Blue Diggings fault.

From stations 76 to 81 the traverse had to be interrupted, because of a small pond. Mine data show that the Daisy fault crosses at about station 80. The drop between stations 85 and 86 is due to the Rosiclare fault, which mine maps show to be at station 86.

The rise at station 89 has not been correlated with any known feature. It may represent a hitherto unknown branch of the Rosiclare fault system, or merely a variation in thickness of the overburden on the Fredonia limestone.

The large rise in the curve which begins at station 115 would strongly suggest a fault were it not for the fact that the rock to the east is certainly Fredonia limestone. At station 116 there is a sinkhole. At other places where the Fredonia likewise occurs on both sides of such an anomaly, the anomaly appears to mark a change in thickness of the overburden. The anomaly at station 115 may have such a cause, but it may represent a fault with the Fredonia limestone on both sides.

Profile 5

The gradual descent of the curve from stations 1 to 9 is apparently due to the transition from the Kinkaid limestone and Degonia sandstone on the west to alluvium on the east.

The rise near station 23 correlates with that near station 30 on profile 4, to the south.

Between stations 38 and 39 the curve drops sharply. This drop occurs just east of the crest of a ridge of Palestine sandstone, and is believed to be due to a fault.

About station 46 an oscillation occurs, with regions of low resistivity on either side. At about this point the geologic map indicates a fault between the Menard limestone and the Golconda limestone—both formations of low resistivity.

The region of high resistivity between stations 53 and 65 is apparently due to a hill capped by Hardinsburg sandstone.

The rise between stations 68 and 69 occurs near the strike extension of both the Blue Diggings and the Argo faults, and it appears to be due to a fault of this system. The further oscillation extending to station 74 may be due to a rather wide fault zone or to several closely spaced faults.

Near station 76 the traverse crosses the Daisy fault, but here the rocks on the two sides are so nearly equal in resistivity that there is not the slightest indication of the fault on the resistivity profile. There are a number of instances of this sort.

The peak at station 82 represents the Rosiclare fault. The peaks of the same order of magnitude as stations 85 and 90 may represent something of importance, but there is no particular reason for supposing that they do.

From stations 93 to 99 there is a stretch of high resistivity, followed by one of low, and east of station 107 the resistivity again becomes high. At stations 94 and 98 the Fredonia limestone crops out. The entire area east of the Rosiclare fault has been mapped geologically as Fredonia limestone, and all of the above noted anomalies may be due merely to the vagaries of the Fredonia (see p. 89). In the low area from stations 99 to 106 no outcrops were observed but some residual sandstone was found. This fact suggests the possibility of a graben in this area but the adjacent profiles offer little supporting evidence.

Profile 6

The oscillation at stations 91 and 92 is unaccounted for. It occurs on the dip slope of the Palestine sandstone, but it does not correlate with anything on the profiles to the north and south. It could be due to a small shear zone.

The drop in resistivity at station 79 occurs near the crest of a ridge. It correlates with a similar feature at station 38 on profile 5, and with other profiles to the north, and a fault is accordingly believed to extend along this scarp.

The high resistivity between stations 59 and 56 appears to be due to the northward extension of the Hardinsburg sandstone.

There is a small oscillation in the curve between stations 50 and 46, about on the strike line of the Blue Diggings and Argo fault systems.

At stations 42 and 35.5 the traverse crosses the Daisy and Hillside faults, respectively, but again the curve gives no indication of their presence.

The curve rises rather sharply near station 25, in a way that suggests the possibility of a fault. A diamond-drill hole, pitching 45° eastward, about 200 feet south of the line of traverse encountered nothing but Fredonia limestone below the surface zone of weathering. The same results were obtained in another hole near station 30. In the east wall of the vein in the Hillside mine, at about the point crossed by the line of traverse, Fredonia limestone is the uppermost formation. It is weathered, however, and is covered with an overburden of residual clay to a depth of nearly 100 feet, and this clay evidently accounts for the low resistivity immediately east of the fault.

Profile 7

Between stations 77 and 66 of profile 7 there is little change in resistivity. Between stations 66 and 65, however, there is an abrupt rise, which occurs in gently rolling topography underlain by Caseyville conglomerate. This rise correlates with similar features on profiles 8 and 10 to the north, and it may represent a north-south fault.

The drop in resistivity at station 61 is an isolated occurrence. Here the topography is somewhat rough, and the low resistivity may be due to that fact.

The decline of the curve from stations 56 to 50 corresponds with the transition from the Caseyville conglomerate to the alluvium of Three Mile Creek.

Station 40 is on the top of a small ridge which is mapped geologically as Kinkaid limestone. Both east and west of this ridge are alluvium-filled valleys. The bedrock in this locality has a regional westward dip of about 500 feet per mile. Across this ridge the resistivity curve is markedly asymmetrical, dropping very sharply between stations 40 and 39, within 100 feet of the ridge crest. This drop may be due merely to the line's crossing formations that have a homoclinal dip, but its abruptness suggests faulting.

The low resistivity between stations 37 and 20 corresponds to an area of alluvium. The rather sudden rise near station 21 occurs at about the eastern boundary of the alluvium and may be due solely to the alluvium, but as it correlates with similar features to the south and to the north it may be due to a fault.

A sudden drop between stations 3 and 4, together with a similar drop on the same ridge of Palestine sandstone noted in the profiles farther south, appears to be due to a fault along the strike of the ridge.

The eastern part of profile 7 was run in 1932. The western part was run in 1934, with an improved instrument that gives somewhat more reliable readings than those obtained in 1932. In 1932 a commutator correction factor was applied, which made the results systematically higher than those of 1934, when its use was discontinued. These facts account for the offset in the curve at station 1, which is common to the eastern and western parts.

As certain instrumental difficulties had not yet been eliminated in 1932, when the eastern part of the traverse was run, it is uncertain whether some of the smaller oscillations are due to geologic causes or to instrumental errors. The sharp dip between stations 12 and 15, however, indicates an anomaly somewhat larger than the adjacent ones and at this place a fault between the Menard limestone and the Golconda formation is shown on the geologic map.

The high-resistivity peak occurring at station 24 is not so clearly accounted for. The geologic map shows nothing that explains it, and it correlates with nothing to the south. In the next profile to the north however, about N. 30° E. from the peak in question, there occurs a similar and more pronounced peak, and it seems probable that both peaks are on a fault zone.

The sharp oscillation between stations 38 and 42 corresponds in position with the Daisy and Hillside faults. It is evidently the result of that fault system, and, though it coincides with none of the faults that are shown on the mine maps, it might be worth investigation.

The low stretch on part of the curve between stations 42 and 48 marks the position of the Hillside fault and of a swampy area covered with waste from the Hillside mine. The sharp rise at station 48 is near an outcrop of Fredonia limestone and is evidently due to the eastward thinning out of the overburden upon the limestone.

Profile 8

Profile 8, like profile 7, was run at two separate times and consists of two number sequences, one extending westward and the other eastward from station 1.

Beginning at the west end of the profile the oscillations between stations 84 and 73 are probably due to faulty readings because of poor ground contacts. As readings between stations 73 and 65 were made with fairly good ground contacts, the rise at station 69 is apparently real and possibly represents a fault.

The large oscillations between stations 65 and 57 are also erratic, owing to the fact that they were taken on a slope of conglomerate that forms a bed in the Caseyville sandstone, on which the contact resistance between the ground and the stakes was so great that not enough current could be made to flow to give reliable readings.

The small peak on the curve at station 43 may not be significant. It appears, however, to correlate with the anomaly at station 40 on profile 7, and both anomalies are interpreted as being on a single fault.

The dip in the profile between stations 37 and 17 represents alluvium. The rather sudden rise at station 14 is interpreted as being due to the same fault that crosses profile 7 at station 19.

The abrupt drop in resistivity near station 2 in the eastern part of profile 8 correlates with similar drops on the profiles to the north and to the south, and is apparently due to a long northeastward-striking fault.

The small abrupt rise between stations 13 and 14 occurs about where the traverse crosses a small valley. The terrain is nearly flat. The asymmetry of the resistivity curve with reference to this valley suggests that the rocks on the two sides of the valley are different, and it is inferred that the valley follows a fault.

The large oscillations between stations 29 and 34 are somewhat west of the main Rosiclare fault, which crosses near station 37. It is about here that the Blue Diggings, Daisy, and Rosiclare faults all converge. The resistivity curve suggests a fault near station 29 and another near station 34. The rise in the curve at station 40 seems to correlate with anomalies on the next two profiles to the north, and is believed, like them, to represent a fault.

Some further light is thrown on this area by the data from a line of diamond-drill holes, furnished to the writer by Mr. A. H. Cronk, Superintendent of the Rosiclare Lead and Fluorspar Mining Co. The line of drill holes runs nearly east-west, only a few hundred feet north of the line of traverse. The holes all pitch eastward or westward, so that successive holes overlap horizontally.

These holes indicate faulting and fluorspar veins near station 35. Another small vein was encountered at considerable depth near station 29 or 30. A drill hole near station 38 or 39 is in gray limestone to a vertical depth of about 200 feet, where it enters cherty limestone. The remaining four holes encounter the cherty limestone at a depth of about 140 feet. The discrepancy of 60 feet occurs close to station 40.

Profile 9

Near the west end of profile 9 the curve rises sharply from stations 82 to 80. The supposed fault passing through station 14 on profile 8 would pass very near station 82 or just to the west of it.

The large anomaly between stations 75 and 70 is interpreted as indicating a fault block bounded by one fault near station 75 and another near station 70. Station 70 is at the crest of a ridge of sandstone that dips gently westward, and station 75 is on the west slope of this ridge. The anomaly just noted correlates with a similar one both to the south and to the north. It is ascribed to a fault, of which there also is geologic evidence: Palestine sandstone is exposed on the ridge and a prospect pit east of the ridge exposed Menard limestone.

The rise in the curve at station 52 probably represents another fault. Geologic mapping shows Hardinsburg sandstone to the east and Menard limestone to the west, with a fault between them somewhere in this vicinity.

The Rosiclare fault is crossed at station 36, but with little effect on the resistivity curve. At station 32, however, there is a small anomaly, which appears to represent the southward extension of a fault that is indicated by the next two traverses to the north and by the anomaly at station 40 on profile 8.

The meaning of the very sharp rise in resistivity beginning near station 23 is uncertain. It strongly suggests a fault with Fredonia limestone to the east, yet there were similar features in some of the profiles farther south where no fault was indicated by mining or drilling data. This rise is regarded, however, as possibly due to a fault.

Profile 10

In going eastward from station 100, at the west end of profile 10, a very sharp rise in resistivity is encountered between stations 89 and 84. This occurs on a hill composed of Caseyville conglomerate. There is no geologic evidence of faulting here but the occurrence of similar anomalies near the same north-south line on profiles 7 and 8 as well as 10 is regarded as indicating a possible fault.

The sharp oscillations in the curve between stations 84 and 77 are due to poor ground contacts on the steep slope of Caseyville conglomerate.

There is an anomalous region of high resistivity between stations 30 and 15, which correlates with similar features on the profiles both to the south and to the north. It is believed that there is a fault near station 30 and another near station 16. Correlation with the profiles to the south and the north suggests the possibility that the oscillations near station 23 may represent a cross-fault striking about north-south.

The geologic map of Hardin County by Stuart Weller shows a fault near station 1 or 2. Wagner placed the same fault more nearly at station −2. At neither place, however, is there much variation in the resistivity curve.

The sharp rise in the curve between stations −16 and −17 coincides exactly with the location of the Rosiclare fault as known from mining data.

The sharp rise in the curve between stations −28 and −29 is difficult to account for except by faulting, though its correlation with the profiles to the north is somewhat uncertain.

The oscillations to the east of station −29 may possibly be explained by faulting, but they are regarded as more probably due to sinkholes in the Fredonia limestone.

Profile 11

The anomalous region of high resistivity between stations 77 and 62 corresponds to the similar region on profile 10 between stations 30 and 15. Faults are indicated near stations 77 and 66, but the location of the one at station 66 is somewhat uncertain. The anomaly actually extends to station 62, but the sharpest break occurs near station 66, and station 66 is in a line with the corresponding points in the adjacent profiles.

The sharp breaks near stations 37.5, 33.5, 30, 25, and 16 may all indicate faults, though their correlation with the neighboring profiles, especially those to the north, is rather uncertain.

The break at 33.5 is near an old shaft on the main Rosiclare fault. The block between stations 30 and 25 has sandstone at the surface, underlain by limestone, and the block contains sinkholes with rims of sandstone. Both Weller and Wagner map this as Bethel sandstone, underlain by Renault limestone and Shetlerville shale.

The break at station 16 is of uncertain significance. East of it are outcrops of Fredonia limestone; west of it is a hill containing loose sandstone. Weller shows a narrow fault block of Cypress sandstone in this area, but Wagner mapped the same rock as Rosiclare sandstone. The sharpness of the break at station 16 seems to favor faulting.

Profile 12

Between stations 79 and 60 profile 12 crosses an anomalous area of high resistivity that is also recorded in the profiles to the south. Faults are tentatively placed near stations 74 and 62, though their exact locations are uncertain.

The geologic map shows a fault near station 47.5 between the Menard and the Glen Dean limestones, but these are both of low resistivity and the fault is not indicated on the resistivity profile. There is possibly a fault between stations 35 and 30, and it is placed at station 32, which is on top of a hill and on moderately level ground. The rise beginning near station 36 can be accounted for as due to transition from limestone and shale to sandstone on a steep slope.

The drop in resistivity near station 28 may indicate either faulting or transition from sandstone to limestone and shale on the east slope of the hill; the latter interpretation seems the more probable.

At station 24 is the Eureka No. 2 shaft, which is close to the Rosiclare fault. The footwall block, to the east, is limestone.

The drop in resistivity near stations 18 to 16, followed by a very large increase near station 13, may be significant, but it is apparently due to the peculiarities of the Fredonia limestone.

Profile 13

The rather large anomaly between stations 89 and 83 on profile 13 was quite unexpected and is entirely unaccounted for by the known areal geology. It occurs in open fields of gentle topographic relief, in which the country rock is mapped as Degonia sandstone. Between stations 89 and 84 the resistivity rises from 5,000 to 125,000 ohm-centimeters, and then suddenly drops at station 83 to 25,000 ohm-centimeters.

After the profile was completed a station was occupied at 83.5 and readings were taken at successive azimuths differing by 30°. The results obtained are plotted graphically above the profile itself. Numerically they are:

Bearing	*Apparent resistivity (ohm-centimeters)*
North-south	16, 300
N. 30° E	26, 000
N. 60° E	37, 100
East-west	170, 000
S. 60° E	134, 000
S. 30° E	14, 600

These results prove that the resistivity peak is real and that the resistivity is highly directional, being very low in a north-south direction and probably greatest in a direction somewhat south of east. This pattern suggests a tabular body of high resistivity, striking a little east of north. There is a similar but more subdued anomaly in profile 14 to the north, in the proper place to correlate with this one. The anomalies may represent two faults, or perhaps a fault zone. The high resistivity suggests mineralization with nonconductive minerals such as calcite, quartz, or fluorspar, and it would bear further investigation.

The high resistivity between stations 72 and 63 is correlated with similar highs in the profiles to the south. Faults are assumed to be present at stations 72 and 63.

The breaks at stations 52.5 and 47.5 also suggest faults, though their correlation is uncertain.

The sharp breaks upward at station 40.5 and downward at station 35.5 both appear to be due to faulting. Faults near these two localities are shown on the areal maps by Stuart Weller (1920) and by Currier and Wagner (1937).

The sharp break at station 26.5 suggests faulting and may represent a branch of the Rosiclare fault. The main Rosiclare fault is crossed near station 22 and is reflected by a small break at station 22.5.

The sharp rise beginning at station 14 is similar to features found in other profiles to the south. It would suggest a fault with Fredonia limestone to the east were it not for the fact that Fredonia limestone is encountered west of this station in the east wall of the Eureka No. 1 shaft. Although this break may be due to faulting, it is more probably due to the peculiarities of the Fredonia limestone.

PROFILE 14

The anomaly between stations 83 and 76 on profile 14 corresponds with that between stations 89 and 83 of profile 13. It may be due to a fault zone or block, and there may be a fault at station 82.5 and another at station 76.5.

The break near station 62 is thought to represent a fault. It occurs near the western boundary of an alluvium deposit, loose sandstone being noted to the west. The high resistivity to the east cannot be due to the alluvium, which has very low resistivity.

The small dip at station 56 may or may not be significant.

The break downward near station 48 is possibly due to a fault, though it cannot certainly be correlated with breaks on the adjacent profiles.

The small break between stations 35 and 34 occurs just about where the geologic map shows a fault with Menard limestone on the west and Tar Springs sandstone on the east.

The large break at station 27 coincides with a visible fault between Glen Dean limestone and Rosiclare sandstone.

The break at station 21.5 may be due either to a sinkhole in the Fredonia limestone or, as appears more likely, to a fault correlating with one at station 26 on profile 13.

The Rosiclare fault is crossed at station 8.5. The drop between stations 5 and 3 is apparently due to a transition from limestone to alluvium.

Profile 15

Profile 15 has a great many breaks, which are generally small, though many of them are larger than some breaks due to known faults. This profile is a quarter of a mile north of profile 14. Profile 16 is a quarter of a mile north of the west end of profile 15, but it swings southward and crosses profile 15 near station 52. Even these two nearest profiles cannot be satisfactorily correlated with profile 15, for they are at considerable distance from it and have few if any specific features in common with it.

There is a small break at station 136, near Three Mile Creek, but it is probably of no significance.

Stations 121 and 123 are near an old open pit mine and two shafts, but there is no trace of disturbance on that part of the resistivity profile.

Quartzite was noted at station 114.5, but the profile there is featureless. The break at station 109.5 is very near a fault that is shown on Weller's geologic map of Hardin County.

A fault that is suggested near station 70 may correlate with the break near station 74.5 on profile 14.

The slight break at station 63.5 seems to correlate with a similar but more pronounced feature at station 62.5 on profile 14. It is possibly due to a fault.

A fault is mapped geologically near station 38, and there is a spring nearby, but the resistivity curve shows nothing.

Most of the ground between stations 40 and 15 is covered with alluvium. The geologic map indicates a complex pattern of faults in this vicinity, but the only one distinctly indicated on the resistivity profile is near station 12. This is evidently a fault between the Palestine sandstone and the Fredonia limestone that is shown on the areal map of Hardin County.

Profile 16

Profile 16 was taken along the Golconda-Elizabethtown highway. Although the profile is plotted as if it were straight and parallel to the others, its eastern part cuts across a number of the other profiles; west of station 85 it runs nearly east and west. The course of the traverse and the positions of the stations are plotted on the base map (pl. 20). Only that part of profile 16 which extends eastward from station 145 is considered here, the western part being discussed on page 113.

The small oscillations in the curve near station 140 coincide with a local outcrop of Fredonia limestone, to which they are apparently due.

The W in the curve at station 111 is near a known fault of very large displacement.

The resistivity peak at station 102 is unaccounted for. It is asymmetrical with respect to a valley at station 100. There may be a fault near station 101, but no correlation has been made between profile 16 and profile 15, to the south.

Weller's map shows a fault near station 88, but the profile shows nothing here except a gradual rise.

The rise in the curve near station 68 seems to correlate with a similar feature in the profiles to the south, and it may mark the location of a fault.

The drop in the curve from stations 53 to 40 mostly coincides with the east slope of a ridge. It may be due to the effect of successively older formations encountered in passing eastward down the slope. The areal map shows a fault near station 39, but there is no indication of this fault on the profile.

The break in the profile near station 35.5 strongly suggests a fault. The sharp rise at station 30 occurs at a known fault.

The break downward near station 26 may not be significant, though it is nearly in line with a similar but more pronounced feature at station 21 in profile 14, and with a break at station 26.5 on profile 13, so that these three breaks may well be due to a fault.

The peak between stations 23 and 19 is unaccounted for, but it may be due in part to underground openings, for there is a known cavern nearby. The Rosiclare fault is crossed near station 18.

The rise at station 3 occurs near an outcrop of Fredonia limestone, and is probably due to the transition from that rock to the Rosiclare sandstone.

Profiles 1 and 2

Although they lie in the eastern part of the Rosiclare district and cross the main Rosiclare fault, profiles 1 and 2 are not a part of the system of profiles hitherto discussed. Both are on the alluvium of the Ohio River flood plain, having been made in the hope of detecting faults that may lie buried beneath the alluvium. The electrode spacing on on them is 200 feet and the stations are 200 feet apart. The main Rosiclare fault changes its strike somewhat abruptly near the Good Hope shaft. To the north the strike is about N. 30° E., to the south it bends to approximately north-south. It was chiefly to determine whether there might be a hidden branch of this fault, striking about S. 30° W., continued under the alluvium, that traverses 1 and 2 were run.

Profile 1 shows only two breaks of any unusual magnitude—a rise in resistivity between stations 8 and 9 and a drop between stations 13 and 16. According to the mine maps the Rosiclare fault was crossed near station 16.

Profile 2 shows no pronounced changes in resistivity. There is a slight drop between stations 6 and 5, where the Rosiclare fault is crossed. The even smaller break between stations 9 and 8 is about in line with the general course of the main fault to the north. There are other small features in this profile, notably between stations 15 and 13 and between stations 3 and 2.

The conditions that affect these two profiles are in several respects unknown. In the nearby Annex shaft the alluvium is about 30 feet thick, and owing to its high electrical conductivity it blurs the resistivity effects due to the formations beneath. It is not known whether the alluvium is uniform in thickness or in texture, but probably it is neither. Areas where the alluvium was thin, so that the more resistive bedrock was near the surface, would be indicated by highs in the resistivity profiles, but so would included pockets of gravel. It is also not known whether, if there is a concealed southwestward extension of the main Rosiclare fault, the same or different formations occur on its two sides. The breaks between stations 8 and 9 of both profiles are in line with the general course of the main fault, and suggest that a branch having the same course may extend under the alluvium. But the evidence is inconclusive, and the problem must be regarded as still unsolved.

WESTERN AREA

The areal geology map of Hardin County by Stuart Weller (1920) shows one fault crossing Wallace Branch diagonally and another extending parallel to it. The resistivity work in the western area has been devoted principally, though not entirely, to making detailed measurements along this branch and following out what appears to be one of these faults.

PROFILE 17

The southernmost of the Wallace Branch profiles is No. 17. In going from west to east, one first encounters a drop in the resistivity curve that extends from station 27 to station 21. This drop correlates with a more pronounced one that occurs in nearly all of the profiles to the north and that is interpreted as due to the principal fault in this valley, which apparently intersects profile 17 near station 23. Between stations 10 and 3 there is an anomalous rise in resistivity, which occurs on the east slope of a ridge, and the asymmetry of the resistivity profile as compared with the topography suggests faulting. A fault is tentatively placed at station 9, and another between stations 3 and 4.

Profile 18

The most outstanding anomaly in profile 18 is the abrupt drop, near the western end, from about 80,000 to less than 10,000 ohm-centimeters. The fault to which this drop is attributed is placed at station 25. In this instance the change in resistivity is entirely asymmetrical with respect to the topography, crossing Wallace Branch without any deviation. Between stations 10 and 4 there is a region of somewhat high resistivity, which appears to correlate with a similar region in profile 17, and faults are placed near stations 14.5 and 6.

Profile 7

Profile 7 is one of the three profiles extending across both the eastern and western areas of the Rosiclare district. Beginning at the west end, there is a very abrupt drop in resistivity between stations 116 and 114, which is correlated with similar features in profiles 17 and 18. A fault is indicated between stations 115 and 114. The small oscillations about station 107 occur near the eastern boundary of the Wallace Branch alluvium, and it may have no other significance, but it is the kind of feature that sometimes marks the crossing of a fault. There is some geologic evidence of faulting near station 104.

The next important anomaly, which occurs near station 79, strongly suggests a fault or fault zone in that vicinity.

Profile 10

Profile 10 is another of the long profiles extending across both the eastern and western parts of the district. The part of this profile extending westward from station 84 was run a second time, in order to verify some of the anomalies which appeared when it was first run and which, it was thought, might possibly be due to errors of measurement. The solid line curve, which ends at station 135, represents the original profile, run in 1932; the dotted-line profile, extending westward to station 145, is the repeat line, run in 1934.

The most striking difference between the profiles is that westward from a point near station 110 they are about 100 feet out of phase;

for example, the notch close to station 116 on the original profile corresponds to the one near station 115 on the repeat profile. This difference is due to the fact that the electrode lines used for measuring the distance from the east end in the two traverses were of slightly different length, the one used in 1935 being the longer.

Another difference between the two profiles is that the resistivity values on the recheck profile are systematically less than the corresponding values on the original profile. The reason for this is that, in computing, a certain correction factor was applied to the data obtained in the original traverse but not to those obtained in the recheck. It was found in 1934 that condensers placed in the potential circuit improved the performance of the instrument, and made the readings somewhat more reliable than those of 1932.

The relative values in the two traverses, it will be seen, are nearly the same; the two profiles, in other words, are nearly of the same shape. A few of the minor oscillations on the original profile occur on the repeat in a somewhat subdued form, but aside from this the two profiles agree in almost every detail. The recheck—one of the very few that were made—tends to show that the results of the work are in the main reliable. As nearly all the ups and downs of the original profile are identifiable also in the recheck, they must be considered as due in much greater degree to geologic features than to errors or to difficulties with the instrument.

Beginning at the west end of profile 10, there is the usual sharp drop followed by a region of low resistivity. A fault is placed near station 143. The small oscillation in the vicinity of station 131 is near a point at which, according to Weller's map, two branching faults intersect. The rise in resistivity between stations 122 and 117 is asymmetrical with respect to the topography, notably to a hill crest of Caseyville sandstone crossed near station 119. This fact suggests that a fault may occur near station 117; the suggestion is not verified, however, by the areal geology, inasmuch as Caseyville sandstone occurs on both sides of the hill.

Profile 19

From a point about 400 feet east of the top of Melcher Hill, profile 19 continues down the eastern slope of that hill and across Wallace Branch. The resistivity rises steeply, though with minor reversals, from stations −10 to −3, and from station −3 to station 0 it steeply descends. The rise appears to be due entirely to the profile's crossing the beveled edges of different strata in going down the slope of Melcher Hill. The fault that appears in the profiles to the south is placed near station −0.5, being supposedly indicated by a notch in the profile at that point.

The small break between stations 13 and 12 occurs in the alluvium of Wallace Branch and may or may not be significant. Near station 9 are some of the workings of the old Miller mine, which according to Weller's map is on a north-south fault. No other notable anomalies occur on this profile.

Profile 20

The region of high resistivity in the western part of profile 20 is in an area of Fredonia limestone, which contains local sinkholes, so that no significance is attached to the oscillations of resistivity in this area. The sharp drop in resistivity that reaches a minimum at station 13 is thought, however, to be due to a fault, which is placed between stations 14 and 15. The rise in resistivity near station 10 strongly suggests another fault. This anomaly does not, indeed, correlate with any on the profiles to the north and south, but the pattern of the known faults, when plotted on the map of the region, indicates that there may be cross-faulting in this vicinity. Definite proof of such faulting, however, would require more detailed mapping than has been done hitherto.

Profile 21

As there is an outcrop of Fredonia limestone at the west end of profile 21, no significance is attached to the drop in resistivity between stations 29 and 27. The sharp drop ending at station 21, however, is thought to be due to a fault between the Fredonia and younger, less resistant formations to the east. This inference is verified to a certain extent by the outcrops in Wallace Branch near station 22, where limestone crops out in the western but not in the eastern meanders of the stream. These meanders apparently swing back and forth across the fault. There are no anomalies farther east in this profile.

Profile 22

In the western part of profile 22 there are two somewhat abrupt drops, one between stations 4 and 5, which is followed by a rise in resistivity, and another between stations 9 and 12. These features appear to mark the crossing of two faults, one near station 5 and the other near station 10.5, which is close to the eastern border of a cemetery. The presence of two faults is also suggested by the forking of Wallace Branch nearby. The westernmost fault would nearly coincide approximately with the western fork of Wallace Branch; the other, which is probably the fault indicated on profile 22 and the profiles farther north, would follow the general trend of the eastern fork. In the eastern part of profile 22 there are indications of faulting at various places between station 28 and the east end of the profile, which is at station 50. Specific features on the profile suggest a fault near station

20, possibly another near 36, a third near 41, and a fourth between 46 and 47—or it might be safer to say that a fault zone apparently extends about from station 36 to station 42. There are too few profiles to make possible any correlation of these anomalies. The profiles to the south do not extend far enough east. Profile 23, to the north, shows anomalies somewhat farther to the west than those on profile 22, but it cannot be assumed that the anomalies on the two profiles are due to the same faults, for, according to Weller the faults in this vicinity strike northeastward.

Profile 23

On profile 23—to begin as usual at the west end—the resistivity rises sharply between stations 60 and 59, east of which there are minor oscillations about a high value, and then a sharp drop east of station 49. The significance of the rise at station 60 cannot be understood without more data for points farther west. The sharp drop between stations 47 and 46, however, appears to represent the eastern branch of the fault recorded farther south. The fault is placed at station 45, which is on the eastern fork of Wallace branch.

The anomalous rise in resistivity between stations 34 and 38 might suggest faulting. The rise occurs, however, where the traverse crosses a small hill capped with Bethel sandstone, which is underlain by the Renault formation, and the rise is symmetrical with respect to the hill crest. Since the Renault formation ordinarily has a lower resistivity than the Bethel sandstone, this anomaly is probably due to the crossing of these formations in their ordinary stratigraphic sequence.

No further anomalies of any appreciable magnitude occur in this profile, though fault breccia was noted at station 4, which is about 400 feet east of the section corner. This is approximately the location of a fault mapped by Weller (1920).

Profile 24

The sharp drop in resistivity extending from station 5 to 11 on profile 24 correlates with similar features in the profiles to the south. A fault is placed near station 10, which again very nearly coincides with the eastern fork of Wallace Branch.

The oscillations between stations 19 and 25 occur in the area of the Bethel sandstone, which may account for them, but, since the oscillations are rather sharp, the possibility of faulting should not be disregarded.

Profile 25

All of the short profiles in the western part of the Rosiclare district that have been discussed already were run in 1934. Profile 25 is the only one that was run in 1932. At that time, some doubt was felt as to the reliability of this profile, because it indicated such abrupt and so frequent changes from high resistivity to low. After the work of 1934, however, the changes in resistivity in the eastern part of profile 25 were found to correlate well with the profiles to the south. The west end of profile 25 is about half a mile west of the Shetlerville road; the east end is at the north-south road along Wallace Branch.

Near the west end of this profile there is a region of moderately high resistivity, followed between stations 63 and 61 by a sharp drop to a region of low resistivity. This drop reflects the topography so closely that it is not possible to say whether there is a fault in this locality or whether the effect is due entirely to topography. Station 63 is at the crest of a hill, capped by Bethel sandstone, the steep eastern slope of which lies between stations 62 and 60. Between station 60 and station 50 the ground is low and undrained. The sharp break in resistivity between stations 62 and 61 may be due to a fault. The rise in resistivity east of station 50 may also indicate a fault, but it may have resulted merely from the eastward thinning of the alluvium. Practically the same feature occurs in corresponding positions on the two succeeding profiles to the north.

No importance is attached to the oscillations in the profile between stations 43 and 32, for here the traverse crosses an area in which there are many sinkholes. The sharp drop near station 31, however, and the corresponding rise between stations 26 and 25, appear to be more probably due to faulting. The intervening low stretch might then represent a graben, or down-dropped block of younger formations, between two blocks of Fredonia limestone; but a similar subsidence might result from a kind of pseudo-faulting, due to the caving in of a large cavern in limestone. There is some geologic evidence that such movements have occurred elsewhere in the district.

Another pair of faults or pseudo-faults is indicated near stations 19 and 14. The steep drop near the east end of the profile correlates with the fault that has been followed from the south. This is placed at about station 1.5—again only a little east of the east fork of Wallace Branch. There is some geologic corroboration of this fault. Near station 5 loose residual limestone occurs in the soil, and in the road at station 1 there is an outcrop of much-fractured sandstone, so that a fault must lie somewhere in between.

PROFILE 26

Profile 26 extends eastward from Big Grand Pierre Creek to the north-south road on the half-mile line of sec. 24, T. 12 S., R. 7 E. The west end of this profile is farther west than those of the profiles immediately to the north or to the south.

The oscillations between stations 120 and 113 suggest faulting, and at station 118 what appeared to be fault breccia in sandstone was noted. Between stations 106 and 85 there are several sharp changes in resistivity that suggest faulting. Two of these, one between stations 106 and 105 and the other near station 101, are in open fields and cannot be accounted for by topography. There is another break between stations 96 and 95, that may indicate a fault. The drop between stations 91 and 90 coincides with a steep sandstone escarpment, and is probably due to the change of resistivity as different strata are encountered at different elevations. The very sharp rise in resistivity between stations 86 and 85, about 300 feet west of the Pope-Hardin County line, probably represents a fault between the Hardinsburg and Bethel sandstones, which was mapped by Weller as passing a little west of the county line.

The region of low resistivity between stations 74 and 61 is of the same character as that noted in profile 25. It coincides with an undrained depression underlain by Rosiclare sandstone and Fredonia limestone. To the east the Rosiclare sandstone and the Fredonia limestone crop out on somewhat higher ground. The depression may represent another case of pseudo-faulting due to caving, but it seems most probably to be on a down-dropped fault block. The sharpness of the resistivity change at the western margin of the area suggests faulting, and the increase in resistivity at the eastern margin, though it might possibly be due to the transition from the alluvium in the depression to the more nearly bare rock farther east, is so abrupt as to indicate faulting.

The oscillations in the resistivity curve between stations 60 and 43 occur in an area known to be occupied by Fredonia limestone and Rosiclare sandstone, with numerous sinkholes. A depression in the resistivity curve between stations 43 and 35 probably represents pseudo-faulting due to caving in of the Fredonia limestone. The resistivity "high" between stations 37 and 33 appears to correlate with a similar but more pronounced feature between stations 25 and 19 on profile 25. A possible fault is indicated near station 30.

The resistivity "high" between stations 25 and 15 appears to correlate with the similar "high" between stations 14 and 2 on profile 25, though its western boundary is not sharply determined. The sharp break at station 18 may represent a fault. On the east side of the "high" the sharp slope downward near station 15 appears to be due to the Wallace Branch fault, crossed by the profiles to the south. The fault is placed near station 13.5, about 100 feet east of the north-south road.

Profile 16

Profile 16, which follows the Elizabethtown-Golconda highway, is the longest continuous profile run in Hardin County. It contains 268 stations, being therefore 26,800 feet, or about 5 miles in length.

The solid-line curve in the western part of the graph represents the profile as originally run. The very large anomaly between stations 259 and 238 was so surprising that it was suspected of being due to some kind of error or to some defect of the instrument. To determine if this were so the line was rerun from station 238 westward and then extended to station 268.. In the original line, the resistivity readings were all taken on one side of the concrete pavement; in the recheck, stations were taken at corresponding points on the opposite side of the pavement. The two curves, though showing minor differences in regard to secondary features, are similar in all essential respects. This result proves beyond a doubt that the anomaly is geologic, not instrumental. It also confirms the recheck on profile 10 in tending to show that the resistivity readings are generally reliable.

Beginning at the west end of profile 16, there is a sharp rise in resistivity between stations 267 and 266. This seems almost certainly to be due to a fault, though its correlation with the profiles to the north and to the south is uncertain. It is inferred that a fault crosses near station 240, on the east side of the anomaly. The precise location of this fault is somewhat uncertain. Its being placed at station 240 is partly because this point is near the break between the high and low resistivities, partly because the point lines up well with corresponding features in the profiles on either side. There is little direct evidence in the surface geology to indicate faulting at this place, though Stuart Weller, on a preliminary geologic map of Hardin County, indicated a fault about here. At station 252 a small shear zone in sandstone is exposed in a road cut, but there is no noticeable break in the resistivity profile, so that the displacement here has probably been small.

The sharp rise in resistivity between stations 231 and 230 marks the eastern boundary of the undrained depression that has been noted in discussing other profiles. This anomaly may or may not be a result of faulting. The oscillations in the resistivity curve between stations 228 and 208 occur over Rosiclare sandstone and Fredonia limestone. The road cut between stations 206 and 205 reveals limestone, and farther east there is sandstone. From station 199 to 197 there is a road cut through massive Fredonia limestone. The low resistivity between stations 206 and 201 is apparently due to a down-dropped sandstone block, which has probably been let down by caving of the underlying limestone.

The sharp break downward in the resistivity curve between stations 195 and 194 apparently represents a fault between Fredonia limestone on the west and an unknown formation on the east. Nothing that corresponds to "high" between stations 25 and 15 on profile 26 and the one between stations 15 and 2 on profile 25 appears on profile 16, though this profile is only 600 feet north of profile 26. The block of high resistivity apparently disappears in this short distance, which seems to indicate a pair of converging faults or else cross-faulting. More detailed work would be required to determine just what has happened here.

The M-shaped oscillation on the profile between stations 181 and 177 occurs in a road cut that exposes thoroughly shattered sandstone. This is just about on the strike of the main Wallace Branch fault, which was followed in the profiles to the south.

No further anomalies of any consequence occur on the part of this profile in the western section of the Rosiclare district.

Profile 27

Between stations 62 and 22 of profile 27 the resistivity varies so erratically that it is almost impossible to pick out significant features. The W-shaped oscillation at station 48 suggests a fault, and it is near a point where two faults intersect, according to Weller's geologic map. The oscillations from station 48 to station 22 are too erratic to interpret. The sharp drop between stations 20 and 19 suggests a fault at the western boundary of the undrained depression, and the rise between stations 10 and 9 also suggests faulting. The intervening area of low resistivity correlates with a similar feature in profiles 16, 26, and 25. The western boundary of the depression is thought to be almost certainly bounded by a fault; faulting on the eastern boundary appears less certain.

SUMMARY FOR THE ROSICLARE DISTRICT

Detailed discussion of the profiles of traverses run in the Rosiclare district has brought out a number of significant facts. It has been made evident, by applying the earth resistivity method, that many known faults are indicated by sharp resistivity anomalies, which in many instances can be used to locate these faults within approximately 100 feet. Many known faults, on the other hand, have been crossed without producing in the resistivity readings any anomaly whatsoever.

Since many geological features other than faults can produce variations in resistivity curves, these curves should be interpreted only with regard to all available geologic information. Care has accordingly been taken, in the foregoing discussion, not to attribute to faulting those features in the resistivity curves that could be accounted for by other facts of the local areal geology or by topography. Only a few major faults not previously known are considered to have been moderately well established by the resistivity method. What appears to be a number of minor faults have been picked up on individual profiles, but, for reasons discussed in the introductory pages, their correlation from one profile to the next is very uncertain.

Another point brought out conclusively is that the work described in this report can only be regarded as reconnaissance. Where detailed information is required on a particular tract of land, the resistivity measurements must be much more closely spaced. One of the most important uses that can be made of the present survey is to indicate areas wherein more intensive prospecting, either by the resistivity method or by more direct methods, may be useful.

The more important features that have been brought out by the study of these profiles are shown on plate 20.

Eastern area.—Beginning on the west side of the eastern area (pl. 20), a possible fault is indicated just west of the township line between R. 7 E. and R. 8. E., on profiles 7, 8, and 10. It runs nearly north and south near station 65 on profile 7, station 90 on profile 10, and station 69 on profile 8.

Another possible fault is indicated near station 4 on profile 5, station 39.5 on profile 7, and station 42.5 on profile 8.

One of the longest faults in the eastern area that has been encountered in this survey is crossed at or near station 53.5 on profile 3, station 30 on profile 4, station 23 on profile 5, station 96 on profile 6, station 19 on profile 7, station 14 on profile 8, station 82 on profile 9, station 29 on profile 10, station 78.5 on profile 11, station 74.5 on profile 12, station 72 on profile 13, station 62.5 on profile 14, station 62.5 on profile 15, and station 68 on profile 16. It strikes about N. 30° E. and is parallel in general to the main Rosiclare fault system.

Another major fault of similar strike is indicated near station 39.5 on profile 3, and station 45 on profile 4. Just north of profile 4 this fault apparently divides into two branches. The western branch is indicated near station 38 on profile 5, station 79 on profile 6, and station 3.5 on profile 7, a little north of which the fault which itself continues about N. 30° E., sends off a branch that strikes due north. The fault striking N. 30° E. is encountered at or near station 4 on profile 8, station 75 on profile 9, and station 24 on profile 10. The north-striking branch occurs at or near station 1.5 (eastern number sequence) on profile 8, station 70 on profile 9, station 16.5 on profile 10, station 66 on profile 11, and station 62 on profile 12.

To return to the first bifurcation, near profile 4 there is some uncertainty as to the exact course of the east branch. It seems reasonable however to correlate station 45 on profile 5 with station 65 on profile 6, station 22 on profile 7, station 29.5 on profile 8, station 37.5 on profile 11, and station 32 on profile 12.

Another fault, located partly on the basis of the resistivity profiles and partly on the basis of areal geology, is crossed at station 13.5 (eastern sequence) on profile 8, station −2 on profile 10, station 40.5 on profile 13, and station 34 on profile 14.

Two short faults are indicated on the western parts of profiles 13 and 14 by a rather unusual anomaly, the exact meaning of which is uncertain but which appears to merit further investigation. The westernmost of these faults is placed at station 88.5 on profile 13 and at station 82.5 on profile 14. The other is placed at station 83.5 on profile 13 and at station 76 on profile 14, and it may cause the anomaly at station 70 on profile 15.

The correlation of the anomaly near station 25 on profile 7 with the one near station 34 on profile 8 is rather uncertain, but these anomalies may represent an extension of the Argo-Blue Diggings fault system.

Another fault is indicated at station 40 (eastern sequence) on profile 8, at station 32 on profile 9, and at station 30 on profile 11, and it appears to be verified by a line of diamond-drill holes near profile 8. An anomaly at station 25.5 on profile 11 may represent the Rosiclare fault.

A rather pronounced break in the resistivity curve at station 23 on profile 9, at station −28.5 on profile 10, at station 16.5 on profile 11, and at station 15 on profile 12 is not satisfactorily accounted for. It may be due to faulting, but the available evidence appears to indicate that it is associated with the peculiar properties of the Fredonia limestone.

In an area a mile across that centers at Stone school, anomalies are so numerous and so irregularly distributed that correlation from one profile to the next is practically impossible, and the geologic map indicates complex faulting in this vicinity. Resistivity measurements in such an area must be more closely spaced than those made hitherto if they are to serve as a basis for reliable interpretations. Only two or three remarks appear to be justified by the available data. Two similar anomalies which occur near the east ends of profiles 4 and 5 may be due to a fault. One of them is near station 113 on profile 4 and the other near station 107 on profile 5. There is also an isolated anomaly at station 99 on profile 5, which may or may not be significant.

Western area.—The main purpose of running the profiles in the western area has been to delineate the fault system along Wallace Branch. Weller's map shows a fault along the valley of Wallace Branch but because of the alluvial cover the precise location of this fault was not known.

At least one fault has been followed along this valley for a distance of about two miles. For most of its length this fault appears to be flanked on the west by Fredonia limestone and on the east by the younger formations of the Chester series. At the points where it is believed to cross the traverse lines there has usually been a sharp rise in resistivity, and if these anomalies are rightly interpreted, the course of the fault along the valley of Wallace Branch has been determined pretty accurately.

The fault is placed at station 23 on profile 17, station 24.5 on profile 18, station 114.5 on profile 7, station 143 on profile 10, station −2.5 on profile 19, station 14.5 on profile 20, station 21.5 on profile 21, station 10.5 on profile 22, station 44.5 on profile 23, station 10 on profile 24, station 2.5 on profile 25, station 13 on profile 26, and station 179 on profile 16. On profile 22, there is also a suggestion of a west branch of this fault near station 5, but this fault is not identified in the profiles toward the north.

The Wallace Branch fault is indicated on the map (pl. 20) by a broken line in the vicinity of profiles 19 and 20, since the resistivity peak near station 9 on profile 20 is not matched on the profiles to the north or to the south. There may be some cross-faulting in the region between profiles 19 and 21, but in order to work this out properly, traverses that were more closely spaced would have to be made in this area.

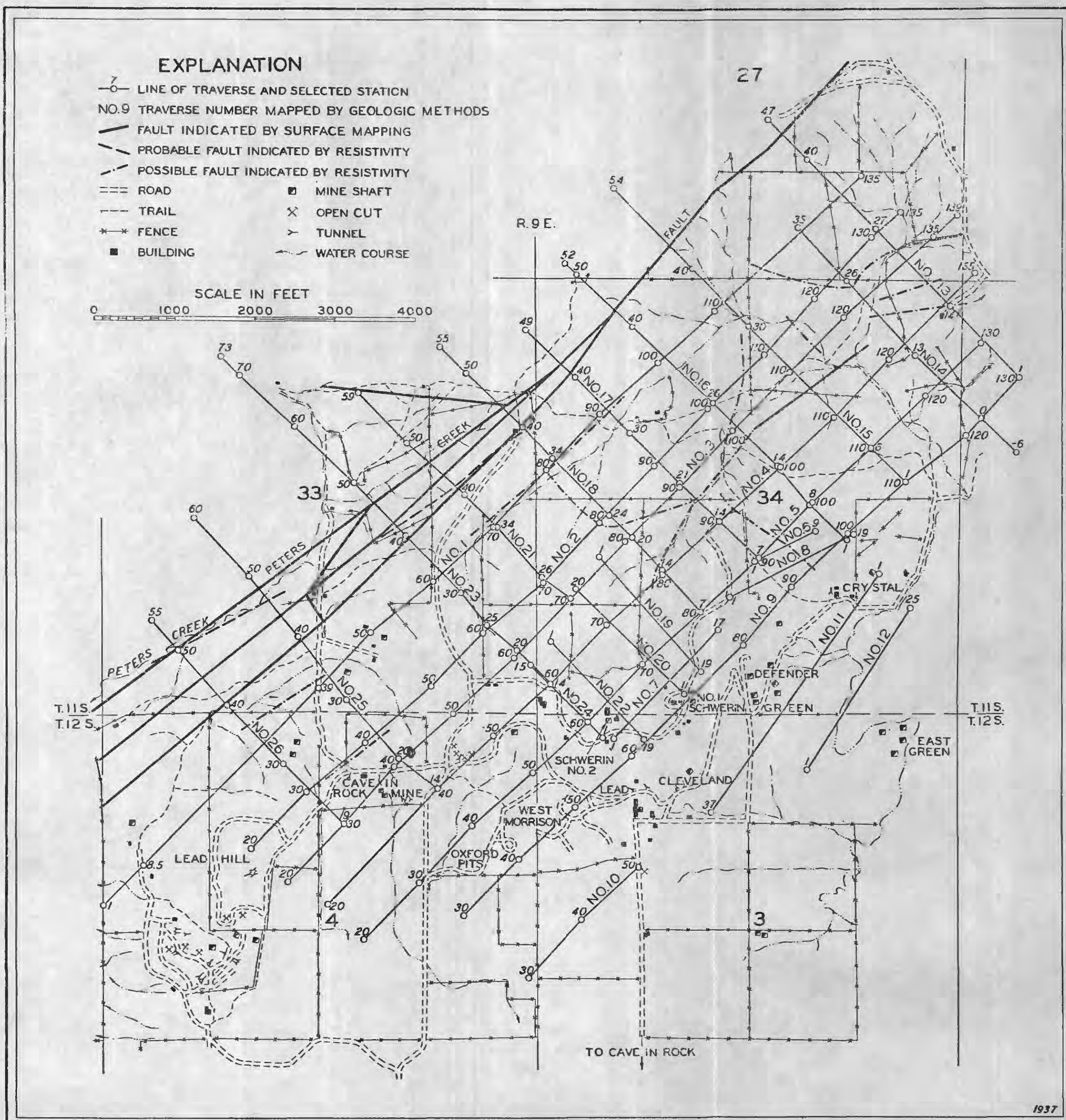
Anomalies that have been tentatively correlated as representing a fault occur at station 10 on profile 17, station 14 on profile 18, station 107 on profile 7, station 134 on profile 10, and station 8 on profile 19. A fault near the old Miller mine is suggested near station 11 on profile 19.

The northeastward-trending fault drawn as crossing profile 22 near station 47 and profile 23 at station 4 is based more on geologic than on geophysical evidence.

Another fault may cross profile 17 at station 4 and profile 18 at station 6.

In the parts of profiles 25, 26, 16, and 27, that extend west of the Wallace Branch Valley, there are suggestions of several faults, though most of the correlations from one profile to another are somewhat uncertain. A fault is indicated near station 48 on profile 27, in approximate agreement with the geologic map of Hardin County, according to which a fault crosses Big Grand Pierre Creek a little west of the western end of profile 26. There appears to be a fault near station 267 on profile 16. On profile 26 there are suggestions of two faults near stations 106 and 100.5 respectively, and of one between stations 96 and 95, but the correlation between these is very uncertain. An anomaly near station 85 on profile 26 is almost directly south of the shear zone noted near station 252 on profile 16 and may be due to the same fault.

All of these four profiles, 25, 26, 16, and 27, show a region of low resistivity bounded rather sharply on both sides by regions of higher resistivity. The western boundary, which occurs approximately at station 62 on profile 25, station 75 on profile 26, station 240 on profile 16, and station 20 on profile 26, is thought to be a fault. The eastern boundary of this same area, which occurs near station 48 on profile 25, station 61 on profile 26, station 230 on profile 16, and station 9.5 on profile 27, may not be a fault, but it probably is, for all the points noted lie on a nearly straight line, and the changes in resistivity appear too sharp to be due to a boundary of alluvium.



MAP OF THE CAVE IN ROCK DISTRICT, HARDIN COUNTY, ILL., SHOWING LOCATION OF EARTH-RESISTIVITY TRAVERSES AND FAULTS.

RESISTIVITY PROFILES OF THE CAVE IN ROCK DISTRICT

The Cave in Rock district includes the northern three-quarters of secs. 3 and 4, T. 12 S., R. 9 E., most of secs. 33 and 34, and the southeastern half, with respect to a line drawn diagonally from the southwest to the northeast corner of sec. 27, T. 11 S., R. 9 E. (pl. 22). The area mapped barely overlaps the west sides of secs. 26 and 35, T. 11 S., R. 9 E.

The western part of the area is crossed from southwest to northeast by the Peters Creek fault zone, which has a northeasterly strike and a downthrow on the northwest. The downthrown block, which is capped by the Caseyville sandstone of the Pottsville group, is topographically the higher. Southeast of the fault zone lies a flat-topped hill, or mesa, of intermediate elevation, called Spar Mountain, which is capped with the Bethel sandstone of the Chester group. On the southeast and southwest, Spar Mountain is bounded by an erosional escarpment, and farther to the southeast and south lies an extensive area in which the country rock is the Fredonia limestone, of the Meramec group.

There is a distinct escarpment between the Caseyville sandstone and the Chester group along the line of outcrop of the Peters Creek fault zone, but this escarpment must be an erosional feature—a fault-line scarp rather than a fault scarp—since the downdropped block, to the northwest, stands higher than the upraised block.

The known fluorspar deposits in this area occur principally in the tract of intermediate elevation southeast of the Peters Creek fault. The fluorspar is mined from bedding-replacement deposits that occur near the top of the Fredonia limestone and that crop out in the escarpment of Spar Mountain. Some of the mines have been developed through horizontal drifts or adits from the face of the escarpment; others are operated from vertical shafts on top of the hill.

In the summer of 1934, a few short experimental resistivity profiles were run in places known to be underlain by bedding-replacement deposits. These profiles revealed a number of unexpected, and to some extent unexplained, resistivity anomalies. It was therefore decided that in the summer of 1935 a controlled grid work of resistivity lines should be run in the area, not so much with the expectation of finding any particular features as with the desire to determine what could be found.

This grid work was confined chiefly to the area underlain by the Chester group between the Peters Creek fault and the area in which the Fredonia limestone crops out. Two series of traverses were run, one on approximately parallel lines extending northeast, and the other on shorter parallel lines extending northwest. These directions conform broadly with the major structural axes of the area. The second series of traverses extended far enough northwestward to cross the Peters Creek fault zone. The average spacing of the lines of traverse in this system was nearly 1,000 feet, while that of the lines running northeast was about 600 feet. Readings were taken at stations 100 feet apart, and an electrode interval of 100 feet was used. The line of electrodes was at all times parallel to the line of traverse.

Topographic and areal maps (pls. 1 and 3) were made at the same time that the resistivity profiles were being run. The lines of traverse were located on this map by placing marked flags at intervals along each line, which were later located by the plane-table survey. The traverse lines are shown on the base map (pl. 22).

DISCUSSION AND INTERPRETATION

NORTHEAST-SOUTHWEST PROFILES

The Cave in Rock profiles (pl. 23) show much more erratic variation from one station to the next than the Rosiclare profiles. Unfortunately, as none of the traverses in the Cave in Rock district were repeated, there is no direct evidence as to how much of this erratic behavior is due to geologic and how much to instrumental causes. It is pertinent, however, to say that profiles 4, 5, 11, 12, 13, and 15 in the Rosiclare area were run immediately after the completion of the work in the Cave in Rock area and with the same instrument; and the fact that these profiles do not show the erratic behavior characteristic of the Cave in Rock profiles tends to show that the causes of this behavior are chiefly geologic.

In any case, the minor oscillations in the Cave in Rock profiles are too numerous to be interpreted individually or to be of any individual significance for our present purposes. In what follows, only the larger changes in the character of the resistivity profiles will be discussed.

PROFILE 1

In profile 1, the northwesternmost of those running northeast (see pl. 23), the changes of resistivity that seem to merit attention are those at stations 11, 20, 53, 80, 100, and 118. The anomaly at station 11 occurs where the traverse is ascending the slope of Lead Hill, and is probably due to the transition from one formation to another or from a thick to a thin cover of soil above the bedrock. The anomaly at station 20 occurs on the north slope of Lead Hill, in an area containing many sinkholes. The steep rise in resistivity between stations 51 and 55 occurs on the southwestern escarpment of Spar Mountain, in which formations of the Chester group are exposed.

The sharp drop in resistivity at station 80 occurs on a very gentle slope. Only Bethel sandstone is mapped at this point, so that if there is a fault here it must have Bethel sandstone in both walls. No other geologic feature has been observed here that would account for this anomaly.

The change in resistivity near station 100 is one of the few anomalies in the Cave in Rock area that can be traced across a large number of successive profiles. It was formerly thought to be due to a fault, but comparison of the resistivity anomalies with the Wagner-Currier geologic maps (pl. 3) has shown that this series of anomalies invariably occurs at or near a northeastward-striking belt of the Paint Creek shale, a rock that has been found to be highly conductive.

The oscillations between stations 110 and 119 occur, in part, where the line crosses two small valleys, and they may be due to changes of resistivity with the irregular topography. One of the valleys is crossed at station 114, and it will be noted that the resistivity on the opposite sides of this valley is not quite the same. This asymmetry suggests that there may be a fault along the valley. The sharp drop near station 118, which occurs well beyond the creek valleys and out on level ground, seems best explainable as due to a fault. Beyond station 119 the resistivity values are almost constant.

Profile 2

Between stations 20 and 80 on resistivity profile 2 there is a great deal of erratic detail, which may be correlated in part with the many indentations of the topographic profile. There is a rather large drop in resistivity between stations 21 and 25, which occurs in the topographic saddle connecting Lead Hill with Spar Mountain, but this anomaly may be due merely to nearby sinkholes.

An increase in average resistivity begins at station 61. The change occurs at the crossing of a small valley, southwest of which the resistivity is high and northeast of which it is low, in a locality of gentle topographic relief. There is no direct geologic evidence of faulting at this place, and the only rock exposed nearby is Bethel sandstone; the topography, however, gives some suggestion of faulting. The creek valley that is crossed at station 61 trends northwest at that place, but about 1,000 feet farther down stream it swings rather sharply to the northeast. This is an unusual stream pattern for nearly horizontal strata, and it may be controlled by small cross faults.

There is another change in resistivity from high to low near station 80, and this change, also, occurs in gentle topography. There is no satisfactory geologic explanation for it other than faulting, though there is no visible evidence of a fault.

The sharp drop in resistivity between stations 114 and 115 occurs where the profile crosses the same small stream that it crossed at station 61, but the stream has made another sharp bend and is here flowing southeastward. In this vicinity the valley is rather steep-sided and fairly symmetrical, and the strata dip very gently to the northeast, so that if the rocks on the two sides were the same the resistivity profile across the valley would also be symmetrical. According to the areal geology map (pl. 3), however, the strata on the two sides of the creek are not the same; Bethel sandstone alone appears on the southwest side, and Bethel sandstone overlain by Paint Creek shale and Cypress sandstone on the northeast side, apparently in normal stratigraphic sequence. The Paint Creek shale is probably responsible for the decline in the resistivity as the creek is crossed. The sharpest decline in resistivity, however, occurs between stations 117 and 119. As this is more than 200 feet from the outcrop of the Paint Creek shale, which dips away from these stations, that formation cannot be held responsible for this particular drop in resistivity. Two other possible causes appear to remain—a fault parallel to the creek, in the Bethel sandstone, or a decline in the depth of the water table.

There is another sharp drop in resistivity between stations 122 and 123, east of which the resistivity is low and very nearly constant. This same feature was observed at and east of station 119 on profile 1. Both breaks occur in open fields, and both are interpreted as being due to the same fault.

Profile 3

Between station 20 and station 30 on profile 3 lies a region of low resistivity, which is followed by one of high resistivity extending from station 30 to station 43. The transition occurs near station 30, which is approximately on the boundary between an area of deep soil and alluvium and a hill slope of bare rock. The resistivity drops between stations 43 and 51 and then rises again. Both the fall and the rise occur on uneven topography, where different strata crop out at different elevations along the line of traverse. If there has been faulting at this locality, its effect is obscured by the variations in resistivity that result from the combined effect of lithologic variety and uneven topography.

The small dip in the resistivity profile near stations 65 and 66 is unaccounted for. It occurs in flat country, and it cannot definitely be correlated with like features on other profiles.

The large drop in resistivity between stations 84 and 88 appears to correlate with similar features occurring near station 80 on profile 1 and station 80 on profile 2. Like these, it occurs in a region of gentle topography, where only Bethel sandstone is exposed, yet it marks the the division between an area of distinctly high and another of distinctly low resistivity, and seems best accounted for as a result of faulting.

In the remainder of the profile, there is a sharp break upward in the resistivity at about station 99, a break downward again at station 108, another break upward at station 108, a break downward at about station 114, and a sharp break downward between stations 133 and 134. The break at station 134 evidently correlates with a similar feature at station 123 on profile 2 and station 119, profile 1. Breaks are more numerous in this part of the profile than in corresponding parts of the other two profiles, and their correlation is uncertain. The break at station 99 occurs where the profile crosses a valley, with respect to which it is asymmetric. The one at station 103 occurs where the same valley is crossed a second time, having made a band between these two stations. The break at station 108 occurs on a gentle slope where the profile runs parallel to the contour line. The break at station 115 occurs 100 feet southwest of the valley that was crossed at station 115 on profile 2, and as there the resistivity is high southwest of the valley and somewhat lower northeast of it. Here again the Paint Creek shale crops out in the northeast bank of the creek, but the major drop in resistivity occurs about 200 feet southwest of the nearest outcrop of Paint Creek shale. A small fault in the Bethel sandstone may possibly connect this anomaly with the corresponding feature between stations 114 and 115 of profile 2. Beyond station 134, the same region of uniformly low resistivity that terminates profiles 1 and 2 is again encountered.

PROFILE 4

From station 20 to a point near station 38, profile 4 extends across a low flat area, containing Fredonia limestone overlain by deep soil, and from there to station 57 it is on the southern escarpment of Spar Mountain, station 57 being at the south brow of the mountain, on its capping of Bethel sandstone. All of the changes in resistivity between stations 20 and 60 can be attributed to variations in the depth of overburden above the bedrock and to the outcropping of different strata along the face of the escarpment. The rise in resistivity between stations 64 and 65, the drop near station 70, and the rise again near station 79 all occur on gently rolling topography, where much of the land has been cultivated. Bethel sandstone crops out at the surface, but there are a few sinkholes formed by caving of the limestone beneath. The sharp variations in resistivity along here do not correlate very well with the adjacent profiles, and they may be due to underground solution channels. The break near station 79 may possibly represent a fault along a small valley which the traverse crosses at this place.

The sharp drop in resistivity between stations 92 and 93 appears to correlate with a similar drop near station 86 on profile 3 and stations 80 on profiles 1 and 2. This correlation implies the existence of either a crooked cross fault or a combination of intersecting faults separating a region of higher resistivity to the southwest from a region of lower resistivity to the northeast.

It is almost impossible to make any rational interpretations of the erratic variations of resistivity northeast of station 93. From stations 93 to 105 the topography is nearly flat; a part of the land was formerly cultivated. At about station 109 the profile crosses a small valley, and at station 117 it crosses a stream in a larger V-shaped valley. From stations 122 to 135 the ground is again almost level.

The rise in resistivity between stations 106 and 109 occurs near the point where the profile crosses a small valley, in the bottom of which there are outcrops of Paint Creek shale, and on both sides of which there is Cypress sandstone. This rise is probably due to the influence of the shale.

The profile is asymmetrical with reference to the stream crossed at station 117, showing successively high resistivity, a drop to low resistivity, and a rise again on the northeast side of the valley.

In this locality the geologic map (pl. 3) shows that Paint Creek shale crops out on both sides of the valley, near station 116 on the southwest side and near station 118 on the northeast side. The shape of the resistivity profile does not very closely correspond to this outcrop pattern. There is no evident influence of the shale on the southwest side, and station 120, on the northeast side, is well up on the hill approximately 60 feet above the place where the map (pl. 3) shows Paint Creek shale. Since there is little or no correspondence between this and the adjacent profiles, the significance of these variations is not clear.

Profile 5

The part of profile 5 between stations 20 and 56 extends from the deep soil cover over the Fredonia limestone across the successive strata that crop out along the escarpment. The Bethel sandstone is encountered near station 52. There is a sharp drop in resistivity between stations 57 and 59. The break in the traverse between stations 62 and 70 is due to a pond. Northeast of station 73 the resistivity rises sharply.

The reason for the area of low resistivity between stations 59 and 73 and for its sharp boundary on the two sides is by no means clear. Part of this "low" occurs in an undrained basin containing sinkholes. In this area a bedding-replacement deposit of fluorspar is being mined at a depth of somewhat more than 100 feet, and there are enough underground workings and diamond-drill holes in the locality to rule out the possibility of any faults of more than a few feet displacement. The surface formation is Bethel sandstone, beneath which the Renault limestone is exposed in a nearby sinkhole. It may be that a combination of thick water-saturated soil in the depression and the proximity to the underlying Renault limestone is responsible for the low resistivity.

From station 89 to station 96 there is a steady decline in resistivity. The northeast end of this decline can be accounted for by the presence of the Paint Creek shale, which is more conductive than the Bethel sandstone, but the beginning of the decline, which is several hundred feet from the shale, cannot be thus accounted for. This drop in resistivity correlates with similar features on the profiles already discussed where no Paint Creek shale is known to occur, and it suggests a possible fault whose location is somewhat uncertain but which is probably near station 93 or station 94. Between stations 96 and 111 the traverse extends across an area of low relief, which is mapped as Cypress sandstone. Across this area the resistivity values oscillate with rather large amplitude, for reasons that are not clear. A creek in a rather steep-sided V-shaped valley is crossed at station 115. According to the geologic map (pl. 3), the bottom of the valley is in Bethel sandstone, above which on both sides is the Paint Creek shale, and the rock of the uplands on both sides is Cypress sandstone. The Paint Creek shale is somewhat lower on the northeast side of the valley than on the southwest side, but this fact is attributed to regional dip. The profile across the valley is asymmetrical, showing high resistivity immediately southwest of the creek and low resistivity for about 500 feet to the northeast. This difference can be partly accounted for by the lower elevation of the Paint Creek on the northeast side of the valley, but it may be partly due to the fact that on the northeast side of the main valley the traverse follows the outcrop of the Paint Creek along a tributary valley for a distance of two or three hundred feet. The rise in resistivity beyond station 122 very nearly coincides with the boundary between the Paint Creek shale and the overlying Cypress sandstone.

Profiles 6, 7, and 8

Profiles 6, 7, and 8 are short, experimental lines run during the summer of 1934, when it was not planned to carry out the more extensive grid work of traverses that were run during the following season.

Profile 6 is a short line, of only nine stations. It shows, in general, a steep decline in resistivity from a maximum value at station 1 to a minimum at station 9. A small valley is crossed at station 6, where there is a slight oscillation in the resistivity curve.

On profile 7 the resistivity is high at the southwest end, but declines sharply, reaching a low value at station 5, and it rises to a high value between stations 13 and 17. The "low" very nearly correlates with a similar area of low resistivity noted in profile 5 and is probably due to the same cause.

On profile 8 the resistivity rises from station 1 at the southwest end to station 12, drops abruptly between stations 12 and 13 from a high value to one less than half as great, and then oscillates about the lower value. The sharp drop occurs at the same small valley that was crossed at station 6 on profile 6. The valley apparently follows a fault, which, incidentally, correlates with the drop in resistivity at about station 94 on profile 5. In each instance, the Paint Creek shale crops out from 100 to 300 feet northeast of the apparent location of the fault and dips away from the fault. This line of anomalies cannot, therefore, be attributed to the influence of the Paint Creek shale.

Profile 9

The line forming the basis of profile 9 is unfortunately located, in that most of it extends along the southeastern scarp of Spar Mountain, so that it continually rises and falls in passing over the eroded edges of the various formations there exposed. The variation of resistivity resulting from this cause alone is sufficient to obscure any anomalies that might be due to faults. The region of low resistivity between stations 60 and 70 correlates with the corresponding regions in profiles 5 and 7 already discussed. The sharp rise in resistivity between stations 94 and 95 is just about on the strike of the supposed fault that crosses the preceding profiles, yet it may be due wholly to transition from the Renault limestone to the Bethel sandstone along the face of the scarp.

Profile 10

Profile 10, which is only 2,000 feet long and extends from station 30 to station 50, is all in an area of Fredonia limestone in which there are scattered sinkholes. The resistivity values fluctuate up and down about a mean value of about 60,000 ohm-centimeters. The variation is of the kind commonly encountered in sinkhole topography and probably is caused merely by the irregularity of the surface of the Fredonia limestone.

Profile 11

Profile 11 extends along the southeastern base of Spar Mountain. It is chiefly on the Fredonia limestone but crosses the outcrop of the "sub-Rosiclare sandstone" zone in two places. Toward the northeast end it extends into the area of the Renault formation. The small peak in the resistivity curve between stations 27 and 23 is about where the outcrops of the sub-Rosiclare sandstone is crossed. The sandstone is crossed again between stations 20 and 15 and causes another peak in the resistivity curve. The lows are over Fredonia limestone. The rise toward the northeast end of the curve is over the Rosiclare sandstone, the Levias limestone, and the Renault formation.

Profile 12

Profile 12 is parallel to and about 600 feet southeast of profile 11. It is almost featureless throughout, evidently because of a deep covering of wet ground and soil and alluvium.

NORTHWEST-SOUTHEAST PROFILES

In discussing the variations of the profiles (pls. 22, 23) that trend northwest, the southeast end of each profile is considered first.

Profile 13

From station 1 to station 13 the resistivity values on profile 13 oscillate about an average value of 70,000 ohm-centimeters. Between stations 13 and 18 there is a region of low resistivity, followed by a return to about the previous average from station 18 to station 24. Then comes an abrupt drop, which continues to station 43, northwest of which the resistivity again rises sharply.

Between stations 1 and 33 the profile is on rock mapped as Cypress sandstone. Through most of the length of the profile the topography is of very slight relief and the land largely under cultivation. The drop in resistivity between stations 13 and 18 indicates possibly a small fault block. The sharp drop between stations 24 and 25 occurs where the profile crosses a small creek with low valley walls. The region of low resistivity to the northwest is the same as that shown on the northeastern sections of profiles 1 and 2. The only probable geologic explanation for this sudden drop appears to be that this creek follows a fault. A short distance downstream the rock is much jointed, as if by local disturbance. The sharp rise in resistivity at station 44 coincides with the Peters Creek fault, with a rolling surface of Hardinsburg sandstone to the southeast and a steep escarpment of Caseyville sandstone to the northwest.

Profile 14

The southeast end of profile 14 is designated station −6. This point is a few hundred feet outside of the area mapped but is a short distance over the edge of the scarp. The low resistivity between stations −3 and −6 is probably due to the influence of the Paint Creek shale, and the succeeding rise to that of the Cypress sandstone. The drop in resistivity near station 8 is symmetrical with reference to a small V-shaped valley, and is probably due to the fact that the influence of the Paint Creek shale is stronger in the bottom of the valley than on the sides. The drop in resistivity close to station 20 is near the crossing of a rather steep V-shaped valley. The valley walls are of Cypress sandstone, but the Paint Creek shale should be only 20 or 30 feet deeper below the valley floor, so that this drop also may be due to the influence of the Paint Creek shale.

A drop in resistivity northwest of station 24 correlates with a similar drop near station 24 on profile 13. It cannot be easily explained except by faulting, since it occurs on almost level ground in an open field.

PROFILE 15

Profile 15 begins, at the southeast, on Bethel sandstone, then crosses the the outcrop of Paint Creek shale near station 2, after which it traverses Cypress sandstone. The low resistivity between stations 2 and 6 is evidently due to the influence of the Paint Creek shale.

In the small valley crossed at station 15, a narrow strip of Paint Creek shale again crops out, probably accounting for the low resistivity at this locality. Beyond station 18 the resistivity again rises sharply, the rise coinciding with a small fault, discovered by Wagner, between the Cypress and the Bethel sandstones.

Between stations 32 and 34 the resistivity again declines sharply. At first this drop was thought to be due to a fault, but it is more probably due to the Paint Creek shale, of which the areal geologic map (pl. 3) shows an outcrop between stations 33 and 35.

The sharp rise beyond station 45 is caused by the Caseyville sandstone which is exposed just west of the Peters Creek fault.

PROFILE 16

The southeast end of profile 16 is on Cypress sandstone. The drop in resistivity immediately following, and the low values of resistivity between stations 3 and 19, are evidently due to the Paint Creek shale, which the traverse crosses along this part of the profile. The traverse continues over a stretch underlain by a thin layer of Cypress sandstone, which causes only a slight rise in resistivity, and then crosses the Paint Creek shale again. The more marked rise in resistivity between stations 19 and 20 probably marks the transition from Paint Creek shale to the underlying Bethel sandstone.

The drop in resistivity near station 32 occurs at a northeastward-flowing creek flowing over sandstone in which there are prominent joints that strike N. 60° E. The Paint Creek shale, as shown on the geologic map (pl. 3), crops out between stations 33 and 34. At the time these traverses were being run, this break in resistivity was thought to represent a fault along the creek. A comparison of the resistivity results with the areal geologic map, however, makes it appear probable that this anomaly is due to the influence of Paint Creek occurring in normal stratigraphic sequence.

The sharp rise northwest of station 46 is due to the influence of the Caseyville sandstone. However, it can hardly represent the Peters Creek fault which, according to the geologic map, crosses the profile near station 43 with Hardinsburg sandstone in the east wall and the Clore limestone, Degonia sandstone, and Kinkaid limestone in the west wall.

PROFILE 17

From station 7 to station 37, according to the areal geologic map, profile 17 crosses Bethel sandstone. Between stations 18 and 20 there is a large drop in resistivity, beginning about 100 feet northwest of a small creek and the resistivity rises again somewhat gradually from stations 22 to 29. There is no visible reason for this low area of resistivity unless a fault, possibly the one shown on the geologic map, extends far enough to cross the profile near station 19, where it would be parallel to the creek and near its left bank. The low resistivity could, in that case, be due to the influence of the Renault limestone, which is moderatively conductive, under a thin covering of Bethel sandstone, and the rise in resistivity to the northwest could be due to the thickening of the Bethel sandstone in that direction. The sharp drop in resistivity between stations 33 and 34 also occurs in the Bethel sandstone area, and might also be due to a fault. At station 32, prominent joints striking N. 65° E. were noted. The bedding here strikes N. 65° E. and has a dip 8° NW., which corresponds to a 14-foot change in elevation per hundred feet of horizontal distance. Should this dip persist, it would cause such an increase northwestward in the thickness of the Bethel sandstone, as would easily account for the observed rise in resistivity.

The downward break in the profile between stations 36 and 37 coincides, again, with the outcrop of the Paint Creek shale as shown on the areal geologic map (pl. 3).

The rise in resistivity at station 48 is evidently due to the influence of the Caseyville sandstone. The two branches of the Peters Creek fault, crossed at stations 41 and 43, had very little influence on the resistivity values.

PROFILE 18

Profile 18 begins at the southeast, in a region of high resistivity. The resistivity drops to a considerably lower level near station 15, which is on the axis of a small valley, and suggestions of faulting along this valley have been noted in some of the other profiles.

The sharp drop in resistivity between stations 39 and 40 occurs at a point where, according to the geologic map, the profile crosses a branch of the Peters Creek fault which here brings Cypress sandstone, on the northwest side, against Bethel sandstone. The Cypress sandstone is probably underlain at no great depth by the Paint Creek shale, and the shale is evidently responsible for the low resistivity on the northwest side of the fault. The geologic map shows three more faults between stations 40 and 50, but they are not indicated by the resistivity values, which are all uniformly low. The tiny break between stations 47 and 48 might be due to one of these faults, but it would not be noticed if the fault were not otherwise known to be present. The sharp rise in resistivity beyond station 51 is apparently not caused by a fault but by Caseyville sandstone cropping out in normal stratigraphic sequence.

Profile 19

Profile 19, one of the short experimental profiles run in 1934, has no features that appear to be significant. It does not show any drop in resistivity corresponding to that near station 15 on profile 18.

Profiles 20 and 21

Profile 20 is another of the short profiles taken in 1934. Profile 21 was run in 1935. Together they make a nearly continouus profile, for the northwest end of profile 20 and the southeast end of 21 almost coincide.

The southeastern part of profile 20 shows very low resistivity along a stretch of 800 feet, in which it crosses the undrained depression. This depression had a similar effect of several of the profiles trending northeast. Beyond station 10 the resistivity rises rather sharply, probably because the rock, with its thin cover of soil, beyond the depression, is much less conductive than the deep wet soil within the depression.

There is a sharp drop in resistivity between stations 35 and 36, near a northeastward-trending valley on both sides of which the surface formation is mapped as Bethel sandstone. A somewhat similar feature was noted near station 34 on profile 17, and the resistivity values oscillate rather widely at the corresponding part of profile 18. These three anomalies may represent a fault parallel to the Peters Creek fault zone.

The final drop in resistivity between stations 41 and 42 suggests a fault near station 41, and this is precisely where the geologic map shows one of the faults of the Peters Creek fault zone. The map shows another of these faults near station 44 and a third at station 46, but neither is indicated on the resistivity profile, unless a small break between stations 47 and 48 represents one of them.

Profile 22

Profile 22, which is another of the short preliminary profiles, closely resembles profile 20, showing low-resistivity for the first nine stations to the southeast and then a rise to a higher resistivity level on the northwest. Mine and drill data indicate that there is no fault of more than a few feet displacement in this locality, so that the change in resistivity is probably due to the transition from deep wet soil to dry, almost bare Bethel sandstone. Where the resistivity is low the Renault limestone, which is relatively conductive, is much nearer the surface than on higher ground to the northwest.

Profiles 23 and 24

Profile 24, one of the short preliminary profiles, shows the same transition from low to high resistivity that was noted in the foregoing profiles.

Profile 23, which overlaps 24 by about three stations, is one of the the later ones. From stations 15 to 41, this profile oscillates within a relatively narrow range, then drops abruptly between stations 41 and 43. The geologic map shows one of the branches of the Peters Creek fault, with Bethel sandstone on both sides, at station 39.5 and another branch at station 42, with Bethel sandstone to the southeast and Tar Springs sandstone to the northwest. This latter fault is probably the one indicated by the drop in the profile, the first one producing no distinguishable effect. A third fault is shown on the geologic map near station 46, but the resistivity profile shows only a very slight rise at this point. Between stations 55 and 68, the profile oscillates about a low resistivity value. The topography between stations 57 and 72 is fairly flat. This western part of the profile extends beyond the area mapped geologically, and also beyond the adjacent profiles. There is a suggestion of possible faulting west of Peters Creek, between stations 57 and 68. The sharp rise in resistivity between stations 72 and 73 reflects the transition from shale to conglomerate of the Caseyville sandstone; there apparently is no fault at this place.

Profile 25

Profile 25 is about 2,000 feet southwest of profiles 23 and 24. Between stations 14 and 35 it passes over a small hill, the crest of which it crosses near station 26. The hill is capped with limestone of the Renault formation, and the Levias limestone, Rosiclare sandstone, and Fredonia limestone crop out on its flanks. As the strata here have only gentle dips, the same formations should be traversed on opposite sides of the hill, and the resistivity values should accordingly be more or less symmetrical with respect to its crest. It was found, however, that the resistivity is high on the southeast side of the hill and low on the northwest side. There is a sharp drop in resistivity near station 23, then an oscillation, and a further drop between stations 33 and 34. Granting that these variations of resistivity may be due in part to variations in the thickness of the overburden, it remains possible that there is a fault near station 23 and another near station 33.

Beyond station 35 the traverse crosses rather low and gently rolling topography. Between stations 45 and 46 there is a small but abrupt rise in resistivity. It is here that the traverse crosses Peters

Creek, and loose quartzite and fault breccia are exposed in the bank of the stream. The geologic map (pl. 3) does not show any fault at this place, but the "high" evidently reflects an unmapped member of the Peters Creek fault zone.

Profile 26

Profile 26 crosses the topographic saddle connecting Lead Hill with Spar Mountain. The ridge crest is at station 30. Except for a little Rosiclare sandstone at the highest part, only Fredonia limestone is exposed in this saddle. Between stations 20 and 45 the profile shows a rather erratic variation of resistivity, with a general descent. A short distance northeast of the line of traverse, near station 25, there is a minor fault with a strike of N. 65° E., at which quartzite is exposed; and only a short distance southeast of the traverse Fredonia limestone, on the other side of the fault, is found in the dump of an old shaft. This fault may extend to profile 25 and may account for the anomaly noted near station 23 on that profile.

There is a break downward in profile 26 between stations 35 and 37. Loose boulders of what appear to be brecciated sandstone are scattered over the surface near station 35, and there may be a small fault extending from this point to the vicinity of station 33 on profile 25.

There is another break downward in resistivity near station 40, and here the geologic map shows a branch of the Peters Creek fault, separating Fredonia limestone on the southeast from Bethel sandstone on the northwest. It shows another fault, between Bethel and Cypress sandstones, near station 45, and this fault probably accounts for the rise in resistivity northwest of that station.

Between stations 50 and 51, about where the traverse crosses Peters Creek, there is again a sharp break downward in the resistivity. Fault breccia was observed in the hillside at station 49.

SUMMARY AND CONCLUSIONS FOR THE CAVE IN ROCK DISTRICT

The resistivity work in the Cave in Rock district was carried out in a spirit of inquiry, its purpose being to see what could be discovered in in an area of minor faults rather than to discover any particular geologic features. The resistivity values were found to vary somewhat more erratically in this area than in that around Rosiclare, but, by disregarding the lesser variations and focusing attention upon the larger, it is possible to detect a certain degree of correlation between resistivity and structure. It has been found, for example, that certain major faults in the Peters Creek fault zone were marked by rather abrupt changes in the value of the resistivity. Other faults, however, because the rocks on the opposite sides are nearly equal in resistivity, are not indicated by the slightest break in the resistivity profile.

It has been found that the Paint Creek shale, which is only about 15 to 20 feet thick, is so good an electrical conductor that wherever its outcrop is crossed there is a large drop in resistivity. It may even have a marked effect on resistivity where it is overlain by the Cypress sandstone, if the sandstone is not too thick. So notable is the effect of the Paint Creek shale that its line of outcrop striking northeastward across the northwest corner of sec. 34, T. 11 S., R. 9 E. was mistaken when the profiles were being run for a major fault, a mistake that was corrected only after careful study of the resistivity data in comparison with the geologic map.

An undrained depression in the southwest corner of sec. 34 contains an area of abnormally low resistivity about 1,000 feet in diameter. Mining and drill-hole data indicate that this area is not bounded by faults, though one small fault of less than 10 feet displacement is encountered in the underground workings beneath the depression. The evidence indicates that the low resistivity in this depression, as compared with that of the surrounding area, is due jointly to its greater proximity to the conductive Renault formation and to its being more deeply mantled with an especially wet residual soil.

Several of the resistivity anomalies in the district, however, are regarded as probably due to minor faults that had not been detected in the course of the geologic mapping, These obscure faults, on which the displacements cannot be more than a few tens of feet, have already been discussed at some length in analyzing the profiles. Considerable uncertainty exists in many cases regarding the correlation from one profile to the next. What seem to be the most probable correlations of these features is indicated on the map (pl. 22), but it should be remembered that these tentative correlations are not the only ones possible.

In the area bounded by profiles 1, 4, 13, and 16 the resistivity values suggest faulting in a somewhat irregular pattern. If such faulting has occurred, the small faults could well act as channels for mineral-bearing solutions, which would make this area a possible source of fluorspar, occurring either in veins or in bedding-replacement deposits. One small fault was discovered in this locality in the course of the areal mapping, and the presence of others is suggested by the resistivity data. These faults being bounded on both sides by the same formation, would have been difficult to detect by geologic mapping unless outcrops of the fault breccias had been encountered.

The interpretations here presented are not offered as conclusive. They do little toward answering directly the question where to look for fluorspar; they are most likely to be useful indirectly, by showing in what area it may be best worth while to prospect further by more direct methods.

APPENDIX [12]

THEORY OF THE WENNER METHOD OF MEASURING EARTH RESISTIVITY

ELECTRICAL RESISTANCE

OHM'S LAW

If an electric current, I, (fig. 23) is made to flow through a resistance, there will be a difference of electrical potential, or voltage, E, between the opposite ends of the resistance. It is found by experi-

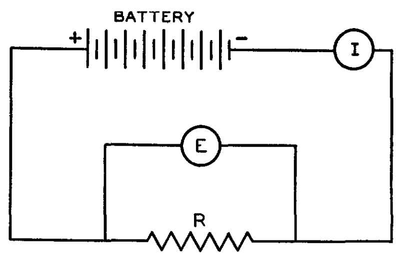


FIGURE 23.—Electrical circuit for measuring the resistance R.

ment that the ratio of the potential difference to the current is constant, at any constant temperature, for any particular resister.

$$\frac{E}{I}=R \text{ (a constant)}, \tag{1}$$

where the *resistance* of the body, R, is expressed in *ohms* when E is in volts and I in amperes. That is, a resistance of one ohm will cause a

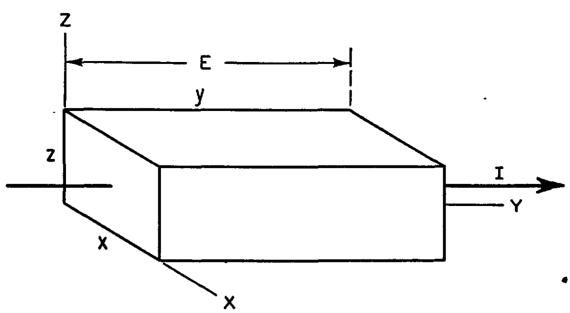


FIGURE 24.—Measurement of the resistance of a rectangular block to the flow of current parallel to the Y axis.

potential drop of one volt for a current of one ampere. This relation is known as Ohm's law.

RESISTANCE OF AN EXTENDED BODY

The resistance of a body varies with its size, shape, and composition, and with the direction in which the current flows through it. Consider a rectangular block of material, as shown in figure 24, with the X, Y,

[12] This appendix is intended to help those engaged in electrical earth-resistivity work to interpret their problems.

and Z axes of coordinates taken along one set of its edges. Let a current I flow through the block parallel to the Y axis, and let E be the voltage drop between its ends.

Under these conditions it is found experimentally that the total resistance of the block is directly proportional to its length parallel to the direction in which the current flows, and inversely proportional to the area of its cross section normal to the direction of flow. Hence,

$$\frac{E}{I}=R=\rho\frac{y}{xz}, \tag{2}$$

where ρ is a constant of proportionality, which differs in value for different materials.

If

$$x=y=z=1 \text{ centimeter},$$

then the block would be a centimeter cube and

$$\frac{E}{I}=R=\rho. \tag{3}$$

Thus ρ, which is known as the *specific electrical resistivity* for a given material, is the resistance offered by a unit cube of that material to the flow of an electric current in a direction perpendicular to one pair of its faces.

Solving equation (2) for ρ we obtain

$$\rho=R\,\frac{xz}{y}$$

or, in words: This has the dimensions

$$\text{Resistivity}=\frac{\text{resistance}\times\text{length}^2}{\text{length}}=\text{resistance}\times\text{length}.$$

When the resistance is measured in ohms and the length in centimeters, the resistivity is in ohm-centimeters. If the length is measured in meters, in inches, or in feet, the resistivity is in ohm-meters, ohm-inches, or ohm-feet, respectively. One system of units is converted to another by means of the same factor that is used in converting the corresponding unit of length. These factors are given in the table following.

Conversion factors for electrical resistivity

Ohm-centimeters	Ohm-meters	Ohm-inches	Ohm-feet
1	0.01	0.39370	0.032808
100	1	39.370	3.2808
2.5400	.025400	1	.083333
30.480	.30480	12	1

551386—44——10

Some materials have different resistivities in different directions, and these are said to be *anisotropic.* *Isotropic* materials, with regard to the flow of electricity, are those which have the same resistivity in all directions. A body is both *homogeneous* and *isotropic* as regards the conduction of electrictiy when its specific resistivity is the same at all points and in all directions.

RESISTANCE OF HALF SPACE TO CURRENT FROM SINGLE ELECTRODE

In the case of earth-resistivity measurements the conductor, instead of being in the nature of an elongate cylinder (such as a wire) or prism, is a mass of practically infinite extent, on the lower side of a bounding surface that may broadly be regarded as horizontal. For purposes of analysis, we shall assume that the topographic surface is a smooth plane surface of infinite extent, and that the earth beneath is of infinite depth and isotropic as regards electrical properties.

Let us imagine that we insert a single electrode into this ideally homogeneous ground and cause a current I to flow through the elec-

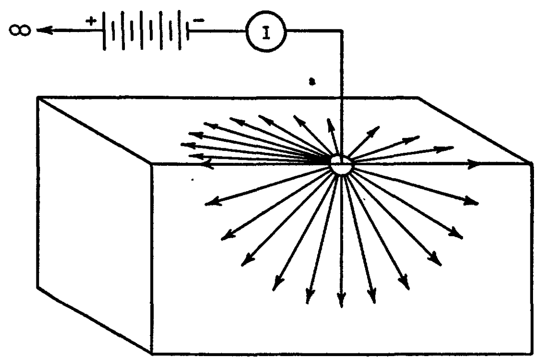


FIGURE 25.—Radial flow of electric current into half space from a single hemispherical electrode (only quarter space shown).

trode into the ground. Since, by hypothesis, all equal radial segments in the ground leading away from this electrode have the same resistance the current will distribute itself equally among them and hence will flow away radially and equally in all directions (fig. 25).

Since the current will everywhere flow radially away from the electrode, the conductor can be thought of as being composed of a series of concentric hemispherical shells having the electrode as their common center.

Let r_0 (fig. 26) be the radius of a small hemisphere centering at the electrode. Let r_1, r_2, r_3, ------------r_n be respectively the outer radii of successive shells at increasing distances away from the electrode. The differences between these successive radii can be made as small as one likes and may be thought of as infinitesimal.

Let ΔR_1 be the resistance of the shell whose inner and outer radii are r_0 and r_1, ΔR_2 that of the shell between r_1 and r_2, and ΔR_n that of the shell whose inner and outer radii are r_{n-1} and r_n. Let R_n be the resistance of the region between r_0 and r_n.

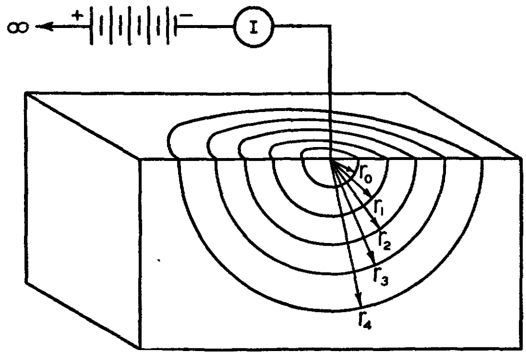


FIGURE 26.—Resistive hemispherical shells about a hemispherical electrode (only a quarter of a sphere shown).

RESISTANCE OF A SINGLE SHELL

The resistance ΔR_1 of the shell between radii r_0 and r_1 corresponds to the resistance of a rectangular prism, since the flow of current is everywhere perpendicular to the surfaces of the shell.

Let ρ be the specific resistivity of the medium. Then, for a thin hemispherical shell,

$$\text{Resistance}=\text{specific resistivity}\times\frac{\text{thickness of shell}}{\text{area of shell}},$$

or

$$\left.\begin{aligned}\Delta R_1&=\rho\cdot\frac{r_1-r_0}{2\pi r_1\, r_0}=\frac{\rho}{2\pi}\left(\frac{1}{r_0}-\frac{1}{r_1}\right),^{13}\\ \Delta R_2&=\rho\cdot\frac{r_2-r_1}{2\pi r_2\, r_1}=\frac{\rho}{2\pi}\left(\frac{1}{r_1}-\frac{1}{r_2}\right),\\ \Delta R_n&=\rho\cdot\frac{r_n-r_{n-1}}{2\pi r_n\, r_{n-1}}=\frac{\rho}{2\pi}\left(\frac{1}{r_{n-1}}-\frac{1}{r_n}\right).\end{aligned}\right\}\qquad(4)$$

TOTAL RESISTANCE

The total resistance, R_n from $r=r_0$ to $r=r_n$ can now be obtained by adding the resistances of each of the shells:

$$R_n=\Delta R_1+\Delta R_2+\Delta R_3+\text{----------}+\Delta R_n.\qquad(5)$$

By combining equations (4) and (5) we get

$$R_n=\frac{\rho}{2\pi}\left(\frac{1}{r_0}-\frac{1}{r_1}+\frac{1}{r_1}-\frac{1}{r_2}+\frac{1}{r_2}-\frac{1}{r_3}+\text{----------}+\frac{1}{r_{n-1}}-\frac{1}{r_n}\right),$$

[13] The product $r_1\, r_0$ is intermediate between r_1^2 and r_0^2, etc.

in which all of the terms except the first and last cancel, leaving

$$R_n=\frac{\rho}{2\pi}\left(\frac{1}{r_0}-\frac{1}{r_n}\right).$$

Now if we let V_0 be the potential at the surface $r=r_0$, and V_n be that at the surface $r=r_n$, and I the current flowing, then by Ohm's Law

$$\frac{V_0-V_n}{I}=R_n=\frac{\rho}{2\pi}\left(\frac{1}{r_0}-\frac{1}{r_n}\right),$$

or the potential drop from r_0 to r_n is

$$V_0-V_n=\frac{I\rho}{2\pi}\left(\frac{1}{r_0}-\frac{1}{r_n}\right).$$

The potential V_n at r_n is

$$V_n=+V_0-\frac{I\rho}{2\pi}\left(\frac{1}{r_0}-\frac{1}{r_n}\right). \tag{7}$$

TWO CURRENT ELECTRODES

Suppose that we vary the above case, where there is only a single electrode, by attaching a second electrode to the ground at a distance

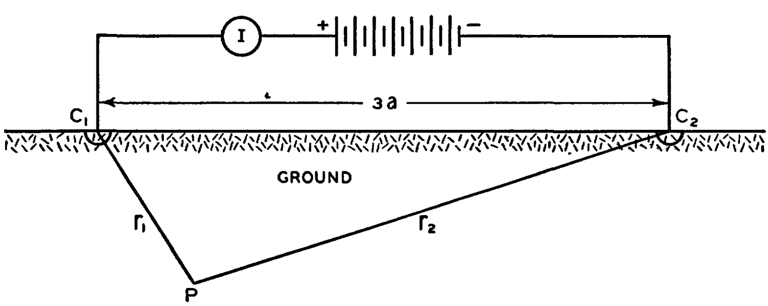


FIGURE 27.—Determination of the potential at an arbitrary point P.

$3a$ from the first. Now through one electrode we let a current I flow into the ground, and through the second we let an exactly equal current flow out. We wish to know the potential at any point P in the conducting medium.

Let C_1 (fig. 27) be the electrode through which the current flows into the ground, and C_2 the one through which it flows out. Let r_1 be the distance of a point P from C_1, and r_2 its distance from C_2. Let $+V_0$ be the potential at radius r_0 from C_1, and $-V_0$ that at radius r_0 from C_2. Let V_1 be the potential at P due to the current flowing from C_1, and V_2 that due to the current flowing to C_2. Let V be the total potential at P.

Now potential is a scalar quantity, and hence adds algebraically. Therefore

$$V = V_1 + V_2. \tag{8}$$

By equation (7)

$$V_1 = V_0 - \frac{I\rho}{2\pi}\left(\frac{1}{r_0} - \frac{1}{r_1}\right)$$

and

$$V_2 = -V_0 + \frac{I\rho}{2\pi}\left(\frac{1}{r_0} - \frac{1}{r_2}\right).$$

Adding, we get

$$V_1 + V_2 = V = V_0 - \frac{I\rho}{2\pi}\left(\frac{1}{r_0} - \frac{1}{r_1}\right) - V_0 + \frac{I\rho}{2\pi}\left(\frac{1}{r_0} - \frac{1}{r_2}\right),$$

or

$$V = \frac{I\rho}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_2}\right). \tag{9}$$

EQUIPOTENTIAL SURFACES AND CURRENT FLOW LINES

When the current I is kept constant the potential at any point P depends only upon the parameters r_1 and r_2. A surface at all points of which the potential is the same is known as an *equipotential* surface. If we set $V = V_c =$ a constant, then equation (9) becomes the equation of the equipotential surface passing through the point P.

$$V = V_c = \frac{I\rho}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_2}\right). \tag{10}$$

To any given value of the potential from $+V_0$ at C_1 to $-V_0$ at C_2 there corresponds a separate equipotential surface. The shapes of these surfaces may be obtained by investigating the family of equations

$$\frac{1}{r_1} - \frac{1}{r_2} = \text{const.} \tag{11}$$

In the vicinity of one of the electrodes, either

$$r_2 \gg r_1 \text{ or } r_1 \gg r_2.$$

In such an instance the effect of the remote electrode becomes negligible and equation (11) is reduced to either

$$\frac{1}{r_1} = \text{const., or } \frac{1}{r_2} = \text{const.}$$

in the vicinity of C_1 or C_2, respectively. Thus the closer to either electrode, the nearer the equipotential surfaces approach hemispheres in shape.

Halfway between the electrodes, r_1 and r_2 are equal, and the equipotential surface here becomes a vertical plane bisecting the region between the two electrodes.

all the others are kept constant. Thus $\frac{\partial \rho}{\partial a}$ means "the rate at which ρ varies when a is changed, z, y, and α being kept constant."

Assuming that we are working on a level topography, we may distinguish the following cases of variation:

Case I. Suppose that

$$\left.\begin{aligned} \frac{\partial \rho}{\partial a}&=0, \\ \frac{\partial \rho}{\partial x}&=0, \\ \frac{\partial \rho}{\partial y}&=0, \\ \frac{\partial \rho}{\partial \alpha}&=0. \end{aligned}\right\} \tag{16}$$

These equations tell us that the resistivity as computed by the Wenner equation is independent of position, of azimuth, and of electrode spacing. This can only be true in a medium that is homogeneous, isotropic, and of infinite extent. A large and deep body of well-mixed water would practically fulfill these conditions.

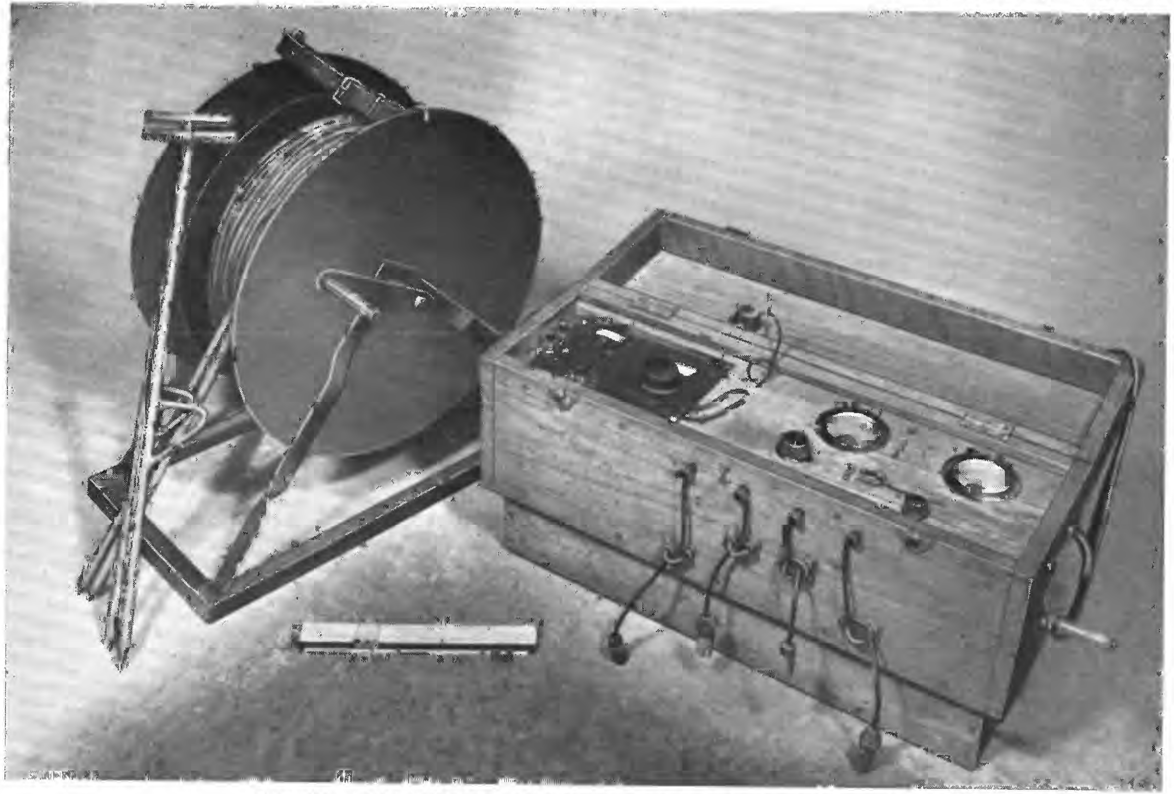
Case II. Suppose that

$$\left.\begin{aligned} \frac{\partial \rho}{\partial x}&=0, \\ \frac{\partial \rho}{\partial y}&=0, \\ \frac{\partial \rho}{\partial \alpha}&=0, \\ \frac{\partial \rho}{\partial a}&\neq 0. \end{aligned}\right\} \tag{17}$$

These equations imply that the medium is made up of homogeneous horizontal layers, but that these layers differ in resistivity. In this case measurement of ρ for a series of different values of a enables one to tell something about the depth to certain layers.

Case III. Suppose that

$$\left.\begin{aligned} \frac{\partial \rho}{\partial x}&\neq 0, \\ \frac{\partial \rho}{\partial y}&\neq 0, \\ \frac{\partial \rho}{\partial \alpha}&\neq 0, \\ \frac{\partial \rho}{\partial a}&\neq 0. \end{aligned}\right\} \tag{18}$$



THE GISH-ROONEY TYPE OF INSTRUMENT USED IN FIELD WORK.

These equations express the most general case of inhomogeneity. They mean that if we take readings at successive stations in either the X-direction or the Y-direction the value of ρ changes, then if we take readings at different azimuths about a single point the value of ρ changes, and that if we vary the electrode spacing the value of ρ changes. It was such a general problem as this that was encountered in the work in Hardin County. There, the quantity principally investigated was $\frac{\partial \rho}{\partial x}$, with α such that the lines were parallel to the X-direction (line of traverse) and a was kept constant at 100 feet. Occasionally $\frac{\partial \rho}{\partial \alpha}$ was investigated in order to determine the strike of some possible fault.

APPARATUS USED

The actual conditions are somewhat more complex than those indicated schematically in figure 29, for the following reasons: At the contact of the potential electrodes (P_1 and P_2) with the ground electrolytic action takes place as in a galvanic cell, producing a difference of potential sometimes as high as a volt between the potential stakes. As this effect is frequently much greater than the potential difference arising from the flow of the current in the ground, it must be eliminated before the latter can be determined, and the apparatus must be so constructed as to accomplish this object.

The instruments used in the work here described (pl. 24) were of the Gish-Rooney type but were built from a design by Mr. F. C. Farnham, of the Missouri Bureau of Geology and mines. The instruments are compact and of light weight, requiring but one operator to make observations.

The wiring of the apparatus is shown in figure 30. The current is supplied by a 90-volt radio B-battery housed in the instrument itself. Provision is made for plugging in an auxiliary "booster" battery for cases where, owing to dry ground or some other cause, extra voltage is needed to drive enough current through the ground. The current flows through a carbon rheostat and then through a milliammeter. The milliammeter is a Weston panel-type instrument having two ranges, 0 to 15 and 0 to 150 milliamperes. Unless too-resistant ground makes it necessary to employ a smaller current, the current is adjusted by means of the rheostat to an even 50 milliamperes at each reading.

After leaving the milliammeter the current flows through one unit of a double commutator, thence into the ground through one of the current electrodes, and out again through the other. It then flows back through the other half of the commutator to the battery. This double commutator consists of two units mounted on a common shaft, which is geared to a hand crank. When the crank is turned the direct current from the battery is made to alternate in the ground,

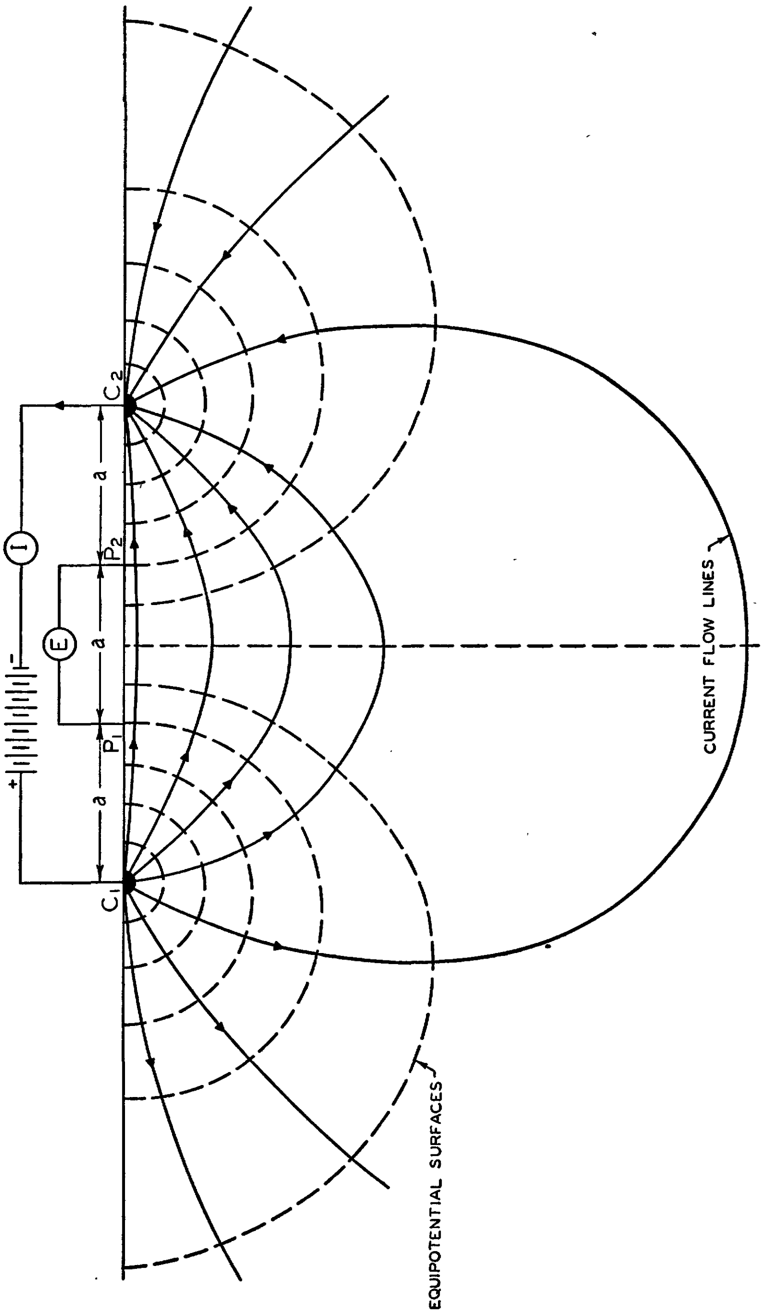


FIGURE 29.—Vertical section along the line of the electrodes showing the lines of flow of the electric current and equipotential surface in homogeneous and isotropic ground.

with a frequency of about 12 cycles per second. The alternating potential difference thus set up between the potential electrodes is rectified by the second unit of the commutator, and is fed to the potentiometer as direct (nonalternating) potential difference. The potentiometer used for measuring the difference of potential, E, is a Leeds and

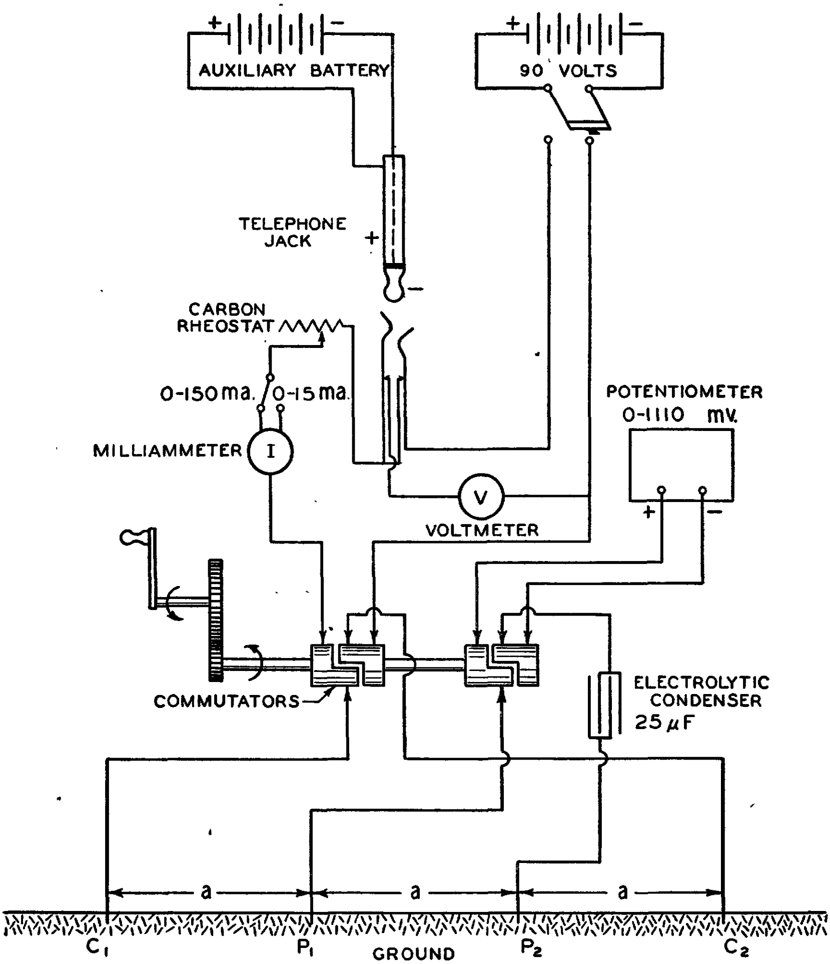


FIGURE 30.—Wiring diagram of the earth-resistivity instrument.

Northrup instrument reading to about 1 millivolt over a range of 0 to 1,110 millivolts.

The purpose of the double commutator is to eliminate the effect of the polarization of the potential electrodes, together with the effect of any stray ground currents that may exist. It was often found that despite the commutation the galvanometer of the potentiometer was too unsteady for a good reading. In such a case, the polarization between the two potential electrodes invariably proved to be a large fraction of a volt. In order to eliminate this difficulty an electrolytic condenser was placed in series with the potentiometer. This condenser completely eliminated any effect of electrode polarization. The condenser used had a capacity of 25 microfarads, but subsequent tests indicate that a much smaller capacity—possibly as small as 1 microfarad—would have done just as well.

The electrodes were of cold-rolled steel, 24 by ⅝ inches, driven about a foot into the ground.

The wire used for the lines was 18-gauge, 20-strand copper, single-conductor Tyrex of 0.2 inch outside diameter. Because of the low tensile strength of copper there was some difficulty with open circuits, and

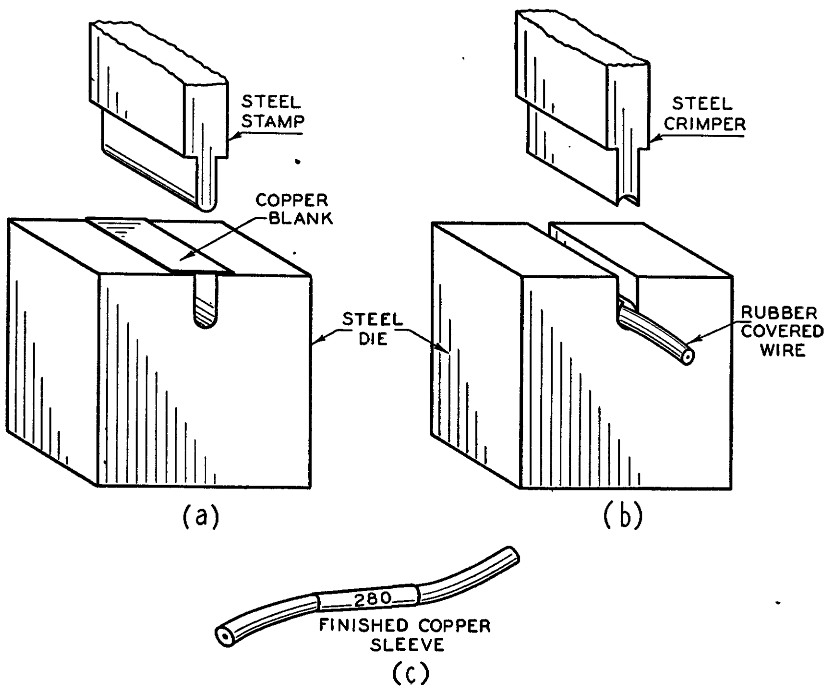


FIGURE 31.—Stamp and die for putting copper sleeves used for markers on insulated wires.

wire having a mixture of steel and copper strands would be preferable. The lines were attached to the stakes by means of spring clips of the type used in charging storage batteries.

The instrument itself occupied a position at the center of the line of electrodes. For a value of *a* equal to 100 feet, the potential lines were each 50 feet long, and the two current leads each 150 feet long.

Reels can be used for the lines, but for an electrode spacing of 100 feet it was found much more convenient to roll the lines up over the hand and elbow.

For some purposes it is convenient to have permanent markers on the lines, making them usable as measuring tapes. Figure 31 shows the method used for putting markers on the lines. Blanks of hardened, light-gauge copper were cut so as to fit snugly around the line. After being stenciled with the proper number, the blanks were placed on the steel die and were driven down with the stamp. Into the sleeve so formed the line was placed and the sleeve crimped on tightly by means of the crimper. Markers made in this way proved entirely satisfactory.

INDEX