A SYMPOSIUM ON THE

GEOLOGY OF FLUORSPAR

PROCEEDINGS OF THE NINTH FORUM ON GEOLOGY OF INDUSTRIAL MINERALS

A SYMPOSIUM ON THE GEOLOGY OF FLUORSPAR

Donald W. Hutcheson, *Editor*

Proceedings of the
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LETTER OF TRANSMITTAL

March 25, 1974

Dr. Wimberly C. Royster
Dean of Graduate School and
     Coordinator of Research
University of Kentucky

Dear Dr. Royster:

The Illinois-Kentucky fluorspar district has produced seventy-five percent of the total United States production. Fluorspar is used as a flux in the steel industry, in industrial chemicals, in the processing of aluminum, and in ceramics.

World-wide interest was generated by this Forum on the Geology of Industrial Minerals. Six of the papers include discussions on fluorspar in Kentucky. These papers should assist in exploration and development of this important mineral, thus aiding in the economic development of Kentucky.

Respectfully submitted,

Wallace W. Hagan
Director and State Geologist

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FOREWORD

The Ninth Annual Forum on the Geology of Industrial Minerals was held in Paducah, Kentucky, on April 26-28, 1973. The three-day program consisted of a business meeting, a symposium of ten invited papers dealing with various aspects of the geology of both United States and foreign fluorspar deposits, and two concurrent all-day field trips to the Illinois-Kentucky fluorspar district. The meeting was attended by approximately 200 geologists, mining engineers, mining company executives, educators, investment analysts, and others, representing 29 states and 6 foreign countries.

The Forum on the Geology of Industrial Minerals was founded as a means of bringing together persons from industry, government, and academia interested in the geological aspects of industrial (nonmetallic) minerals and their utilization. The first Forum was held in February 1965 in Columbus, Ohio, with subsequent meetings in Indiana, Kansas, Texas, Pennsylvania, Michigan, Florida, Iowa, and most recently, Kentucky. The theme of the meeting is determined by the host organization and usually reflects the local resource base and mineral industries. Previous meetings have discussed the geology of such commodities as limestone, dolomite, cement raw materials, mineral aggregates, phosphate rock, building stone, gypsum, and clays. A list of publications containing papers presented at previous Forum meetings is tabulated inside the back cover of this volume.

The Ninth Forum, hosted jointly by the state geological surveys of Illinois and Kentucky, provided a unique opportunity to hear some of the world's most experienced fluorspar geologists discuss various aspects of the geology of stratiform and vein deposits and visit the largest fluorspar-producing district in the United States.

Fluorspar is the commercial name for the mineral fluorite, the most important source of fluorine. It has wide application in the production of aluminum, steel, many ceramics, and a variety of chemicals which are manufactured for a large number of industrial products.

Paducah, located near the northern tip of the Mississippi Embayment, is only a 30-minute drive from the Illinois-Kentucky fluorspar mining district. This district, which has been active for more than a century, has produced approximately 75 percent of the total fluorspar mined in the United States.

The papers included in this volume are the printed versions of the talks given at the symposium. They provide an insight into the geological parameters which are related to the occurrence of fluorspar deposits. Thus, they should aid in planning future exploration programs. In addition to assisting in the prospecting for and development of fluorspar resources, this volume will be a valuable reference to students of earth sciences interested in mineral occurrences.

The last day of the Forum was devoted to two concurrent field trips to both the Illinois and the Kentucky portions of the fluorspar mining district. The Illinois excursion was the principal field trip, featuring underground visits to mines of Ozark-Mahoning Company, Mining Division, and Minerva Oil Company, Fluorspar Division, to observe bedded and vein ore occurrences. The trip to the Kentucky portion of the district was arranged for those who could not be accommodated on the Illinois trip. The Kentucky trip was restricted to salient surface geologic features, including areas of Pennwalt's Dyer's Hill mine (now inactive), the new Cerro-FFL project (currently under development), high-calcium ledges of the Fredonia Member of the Ste. Genevieve Limestone (a prominent host rock for fluorspar ore), and exposures of portions of major fault systems.

The writers acknowledge with thanks the assistance and cooperation of the authors of the papers, field-trip leaders, companies who permitted access to properties, fellow staff members, and others during the preparation for and conduct of this symposium on the geology of fluorspar.

Preston McGrain, Kentucky Geological Survey
Robert L. Major, Illinois State Geological Survey
Co-chairmen, Steering Committee
Forum on the Geology of Industrial Minerals,
1972-73

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FLUORINE RESOURCES—AN OVERVIEW

GILL MONTGOMERY

Vice-President and General Manager
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By the simple and unhonorable process of seniority and longevity, I am approaching the status of "old timer" and guess I am about the oldest fluorspar operator in the Illinois-Kentucky field, at least in the engineering and management end of the business. I had my first hand for fluorspar in churndrill cuttings in Hardin County in 1941, and enjoyed the unfolding development, by drilling, of what has turned out to be one of the largest orebodies in the United States, Minerva mine No. 1, north of Cave in Rock, Ill. This mine has produced well over 3 million tons of fluorspar ore, and at least half this much is blocked out for future years. Being nurtured all these years by such a wonderful orebody does, not qualify me for the title "Mr. Fluorspar"; it just makes me the oldest fluorspar manager still around.

However, welcome to the grand old "mother lode country of fluorspar," the Illinois-Kentucky district, composed essentially of Crittenden and Livingston Counties, Ky., and Hardin and Pope Counties, Ill., an area about 60 miles north and south by some 35 miles east and west. In this district, fluorspar has been more or less continuously produced since the 1870's, although it was only a minor item of commerce until the First World War, when a major demand developed for metallurgical gravel fluorspar as a flux in the open-hearth method of steelmaking. This consumption continued to be the principal use until the 1950's, when the rapidly expanding fluorine chemical business, and the use of synthetic cryolite and aluminum fluoride in the aluminum industry, reached major proportions. Today, fluorspar is considered one of the nation's most strategic minerals. Fluorinated hydrocarbons are part of our modern way of life, being the refrigerant used in air conditioning and the principal aerosol used in most spray products. Fluorine is necessary in the manufacture of high-test fuels such as alkylated aviation gasoline and is necessary in the synthesis of fluorcarbon polymers such as DuPont's Teflon and a whole family of specialty plastics and coatings. It is required in the separation of uranium isotopes, and is, therefore, essential to our entire nuclear power program. Substantial quantities are also being used in the manufacture of flint glass, fiberglass, enamel frits, and glazes, where it is used as a flux. It is in increasing use as a welding-rod coating and in several abrasive products.

Fluorspar, the common name for the mineral fluorite (CaF_2), is the subject of our discussions today, as we consider where it came from, when it arrived, what host rocks it favors, and what geologic structures have favored its accumulation. We will also consider how to go about finding it, as we look at increasingly sophisticated methods of exploration.

The United States is producing about 20 percent of its consumption requirements. Production amounts to about 250,000 short tons per year, and we consume about 1,200,000 tons in various forms and grades. Most of our fluorspar is imported from Mexico, usually either as a ground flotation concentrate (97 percent CaF_2) or as the lump or gravel form, running between 82 and 85 percent CaF_2 and usually classed as 70 percent effective metallurgical fluorspar. Other principal sources of imported fluorspar, essentially the acid grade, are, in order of importance, Spain, Italy, England, and South Africa. Potential sources of imports from important new mining areas are Thailand, Brazil, Argentina, Tunis, Kenya, Mozambique, and Southwest Africa.

The price of domestic fluorspar ranges from $87 per ton for acid-grade material dried and in bulk, f.o.b. cars, Rosiclare or Junction, Ill., to domestic metallurgical gravel (about 82 percent CaF_2) which sells for $60 per ton. Most of the ceramic grades are prepared in this district. No. 1 ceramic is classed as 95 percent CaF_2, and sells

at $82 per ton. No. 2 ceramic sells for $77 per ton when it is 90 percent CaF_2. This same material is also made into pellets and briquettes for the basic oxygen process steel plants, and is cast into bricks at Rosiclare by the Cleveland Flux Company for sale as flux to the foundry industry.

Now, I shall say a few words about the mining of fluorspar. Fluorspar deposits are generally of two principal types: the bedded replacement of limestone, usually of Chester or Ste. Genevieve age (Late Mississippian), and veins occupying tension fractures. Fluorspar veins of commercial interest have been found in Lower Pennsylvanian sandstones, throughout the entire Chester section, and well into the underlying St. Louis limestone. The veins usually bottom in calcite with fluorspar stringers, indicating a hydrothermal source and a vertical zonation of deposition related to favorable temperature and pressure for crystallization of fluorite. The bedded formations terminate abruptly at their margins. Most of the favorable bedded deposits are along a band of minor southwest to northeast fissures, parallel to the Peters Creek fault, northwest of Cave in Rock, plus one mine near Joy. Compressional structures are observed in bedded deposits, indicating almost horizontal thrustal pressures from the southeast which tended to close the fracture systems and inhibit the upward migration of ore-forming solutions through shale sections to form veins. It has become interesting to speculate that the plate-tectonic movements recently used to explain the crumpling of the Appalachian Mountains, perhaps when Africa came over and bumped into North America, may have exerted horizontal crustal forces on this district near the end of Paleozoic time. The rest of the deposits of the district are essentially fissure veins in tension fracture systems. The major faults seem to contain too much gouge to favor commercial mineralization. Associated with fluorspar in many of the mines are important quantities of zinc, as sphalerite, and lead, as galena. Barite is a common constituent in various localities, in both bedded and vein deposits. Efforts are now under way to develop economic outlets for barite products. Strontium minerals occur in some barite deposits, as does witherite. Limestone of road-rock quality is a byproduct of the heavy-media separation plants.

In the bedded deposits, which usually range in thickness from 4 feet to over 20 feet, random room-and-pillar mining is the rule, and practically all of it is now done by rubber-tired diesel equipment. Most of the drilling is done by compressed-air rock drills, usually on two-boom Jumbos, and most of them are self-propelled by diesel motors. Drilling is done mostly with tungsten carbide bits. Ammonium nitrate-fuel oil mixtures are used for blasting the ore in the relatively dry faces, but nitro starch and slower dynamites are used in wet locations. Most loading is now done by rubber-tired diesel muck-haul units, either of the Wagner or Eimco types, ranging in bucket capacity from 1 yard to 5 yards. Most of the hauling is done by diesel trucks to shaft-bottom crushing stations. These range in capacity from about 6 tons to 18 tons. Roof bolting carriages, personnel wagons, underground roadgraders, and utility vehicles are usually rubber tired and equipped with diesel engines.

Roof spans between pillars vary from as little as 8 feet where the roof is shaly, to over 30 feet where there are massive sandstone roofs such as the Bethel sandstone. Roof bolting is necessary or prudent throughout most of the room-and-pillar operations. Such mines customarily have comparatively little water in them unless they are close to the surface. Ventilation is by forced air through air shafts or drilled ventilation holes, and in dead-end areas additional air is supplied through woven plastic ventilating tubing of various diameters by booster fans. There are no explosive gases present. In several areas, the connate waters of freshly drilled orebodies are noted to be saturated with hydrogen sulfide gas, and its dispersion requires additional ventilation. The mine waters are nontoxic and are used for household and stock-watering purposes, as well as water supplies for fluorspar-processing plants.

Three mines are currently under development in the district. The Cerro Corporation, Barnes tract development, near Salem, Ky., has recently reached its total depth of 800 feet and is developing on its haulage level; at the same time it is constructing an adjacent heavy-media separation and flotation mill. The Ozark-Mahoning Company is developing the haulage levels at its Knight mine west of Rosiclare, where it has also constructed a

heavy-media plant. The Minerva Oil Company, Fluorspar Division, is raising an air shaft at its Spivey development in northern Hardin County from the 300-foot level prior to sinking its production shaft to about 650 feet.

At the present time, only two companies are operating processing plants in the fluorspar district, these being Minerva Oil Company and the Ozark-Mahoning Company. Minerva has its principal mill 5 miles north of Cave in Rock, and a supplemental mill, the Crystal plant, is located 4 miles northwest of Cave in Rock. Both have heavy-media preconcentration units followed by flotation, and both can also save lead and zinc sulfides. Ozark-Mahoning has its central mill at Rosiclare, and most of the ore from its field shafts is preconcentrated at a heavy-media mill northwest of Cave in Rock. This does not apply to the vein ore from its Barnett shaft.

The Calvert City Chemical Co. recently closed its mill at Mexico, Ky., following the closure of its Shouse mine near Joy, and its Babb mine near Salem. The Cerro Corporation is constructing a mill north of Salem and plans to be in production by the end of 1973. On Spar Mountain, northwest of Cave in Rock, Robin Hastie & Sons are reconstructing a heavy-media mill brought from Marion, Ky., where it formerly operated for Kentucky Fluorspar Co. Omar Austin & Sons and M. L. Conn & Sons both have logwashing plants which may operate this summer. There are several other logwasher operations both in Illinois and Kentucky which operate intermittently. Much of their product is sold to flotation plants unless they can make metallurgical gravel fluorspar for direct sale.

Business at the present time is a little slow for the U.S. fluorspar industry due to what we hope is a temporary oversupply situation, worldwide, with a resulting downward pressure on prices of imported fluorspar. Only 2 or 3 years ago there was a world fluorspar shortage. This encouraged much new exploration and mine development effort, which was all too successful, resulting in a lot of extra production coming onto the world market at the very worst time. Within the past year, we have seen a sharp dropoff in the consumption of fluorspar by Japan, as well as western Europe, and a slowdown in the use of fluorspar in the aluminum industry, and in the steel industry to some extent. Now there is a strong business recovery underway, and we can only hope that this will be worldwide and that it will soak up the surplus supplies which are presently giving us a lot of headaches.

The pressure of cheaper material from the Mexican border has been particularly painful to the many small fluorspar producers and potential producers in the Western States. There is a lot of fluorspar in Colorado, Idaho, Nevada, Utah, New Mexico, Arizona, west Texas, and southern California. Unfortunately, there is not much market out there. Most of the market is along the Gulf Coast, the Atlantic Coast, around the Great Lakes, and along the interior waterways. Therefore, these western operations have been at a distinct disadvantage as compared to the Illinois-Kentucky district, lying as it does on both sides of the Ohio River with its barge traffic, and near to several consumption centers.

I hope this has given you an overall glimpse of the industrial mineral in the proper framework for the geological discussions that follow, not all of which will essentially agree with one another.

THE ENVIRONMENTS OF DEPOSITION OF FLUORSPAR

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ABSTRACT

Fluorspar deposits with some degree of commercial significance occur throughout the inhabited world. They occur in many kinds of geologic environments, and give indications of having been formed under a wide range of geologic conditions. The commonest environments are fissure veins, stratiform deposits, replacements of carbonate rocks along contacts with acid intrusive rocks, stockworks in tectonically shattered zones, carbonatites, residual concentrations derived from the weathering of primary deposits, and gangue mineral occurrences. Less common modes of occurrence include fillings in breccia pipes, replacements in large inclusions in granite, fillings of cave-like open spaces, and pegmatites. Many fluorspar districts contain several kinds of deposits in close proximity, such as veins, stratiform deposits, and residual concentrations. There is no single characteristic geological mode of occurrence in many localities, so that careful attention should be given to the examination of all possible environments present.

This paper is the joint product of several of the members of the Geology Section of the Purchasing Department of the DuPont Company, and most of the data to be presented were developed by our own people during field investigations, with only a small part being taken from publications.

The plan for this presentation is to treat some generalities first, then to list the common and less common geologic environments of deposition, and then to cite brief examples, with brief descriptions, of each. Various fluorspar districts and areas in the Free World, including those to be dealt with by following speakers, will be touched upon here. However, because of time allowed, it will not be possible to go into much detail, and it is hoped thereby that these descriptions will not conflict with or subtract from those which you will hear later.

It is difficult to illustrate a subject such as this because of its very general nature. There will be a few slides of fluorspar districts in Spain, Mexico, and Brazil, but they are intended more to put you in the mood than to illustrate specific features of this talk. In most cases there will be no commentary devoted to individual slides.

The principal reason for giving a paper of this sort is to summarize in collected form features of fluorspar deposits which might prove helpful to those of us seeking new deposits in new areas, to help us keep in mind sites of possible ore occurrence in established districts, or to help us interpret the odd-looking or enigmatic results of exploratory drilling. In other words, the main concern of this paper is establishing guides to finding and identifying fluorspar deposits. Much has been said about this subject before, and the basic facts are well known to many of you already. However, fluorspar comes in so many forms difficult for the field geologist to recognize and appreciate that an iteration of characteristically favorable sites is not amiss, to help keep the senses alert and tuned to fluorspar, as it were. When presented with coarsely crystalline masses of a heavy mineral with the characteristic octahedral cleavage and the common blue, green, purple, or yellow colors, one has little difficulty in thinking "fluorspar." But when one is shown dense chalcedonic forms with brown, black, red, or gray coloration and no cleavage, one may not think "fluorspar" so readily.

The Ozark-Mahoning Company had a display of fluorspar specimens from deposits all over the world. Many of these specimens were so atypical in appearance as to be baffling, and the message to be gained was to think "this could be fluorspar" when handling any knife-soft, heavy, chalcedonic-textured materials.

Fluorspar occurs in many types of geologic environments and has been formed under a wide range of geologic conditions. Some types of environments are not known to have provided deposits of commercial grade or size. For example, fluorite is an accessory mineral in some igneous rocks such as the radioactive quartz bostonite of Central City, Colorado, and the fluoritic granites of Conway, New Hampshire, and Nigeria.

The commonest environments for the deposition of fluorspar are:

1. Fissure veins, in many kinds of country rock, notably granite and limestone.
2. Stratiform deposits in carbonate rocks.
3. Replacements in carbonate rocks along contacts with intrusive acid igneous rocks.
4. Stockworks or fillings in sheared or tectonically shattered zones.
5. Carbonatites and alkalic rock complexes.
6. Residual concentrations from the weathering of primary deposits.
7. Gangue mineral occurrences.

Less common, but nevertheless in some cases of major commercial importance, are:

8. Fillings in breccia pipes of explosive or collapse origin.
9. Replacements in massive inclusions in granite.
10. Fillings in open spaces.
11. Pegmatites.

Still less common, but possibly of some importance, are:

12. Deposits in lake sediments.

In some areas fluorspar is found in a combination of environments. A case in point is the nearby Illinois-Kentucky district where there are fissure vein deposits as well as stratiform replacement deposits, plus some that are a little of both; in the past there were also rich residual deposits of significant tonnage. As a matter of fact, many of the residual deposits were developed from primary vein deposits which were found to be too lean to support mining operations. In considering new areas, one should keep in mind the fact that a combination of types of occurrence may exist.

Another example of this principle is afforded by the Lost River district in Alaska, which has been much featured in the mining press of recent months. According to the published accounts, in one area fluorspar has partially replaced limestone where it overlies an intrusive granite dome. In another area it occurs as irregular replacements in brecciated and porous limestone beds adjacent to a thrust fault. In a third area the fluorspar occurs in veins and pipes in limestone and dolomite, and a fourth deposit consists of a fluoritized zone in slate. In addition, fluorspar occurs locally in skarn along limestone-granite contacts. The general background at Lost River is one of a series of highly faulted and brecciated limestones intruded by stocks and dikes of hydrothermally active granite carrying substantial amounts of fluorine, plus tin, tungsten, and beryllium.

Fissure veins, usually along faults, are probably the commonest of all environments in which fluorspar deposits occur the world over. Silica, calcite or other carbonates, iron, lead, and zinc sulfides, and in some areas barite, are typically associated with fluorspar deposits. In some vein deposits, as in the Rosiclare district, fluorite appears in many places to have replaced a prior vein filling of calcite. In some veins replacement bodies have formed out into the wall rock at intersections with favorable beds. In some veins a notable proportion of the total tonnage mined comes from these replacement bodies, so much so that it is common practice to orient exploratory drill holes so as to cut the vein at those favorable zones. Ore shoots are normal features of fissure vein deposits.

Some of the world's great vein deposits include the following: the Osor deposit in northeastern Spain, the Torgola deposit in northern Italy, the Muscadroxiu-Genna Tres Montis vein system in Sardinia, the Longstone Edge-Sallet Hole deposit in England, and, of course, the Rosiclare-Goodhope vein system in southern Illinois. The principal vein in Brazil's Criciuma district is also notable.

The Osor vein near Gerona, Spain, on the southern flank of the Pyrenees, has been known since the turn of the century. It is a major east-

west fissure filling in porphyritic granite which contains lenticular bodies and schlieren of biotite gneiss and schist, and which is cut by narrow alaskite and pegmatite dikes. The strike length is about 1 kilometer. The dip is nearly vertical to a depth of 40 meters, where the vein branches like an inverted "Y." The north branch, the more persistent of the two, continues downward at a dip of 60 to 70 degrees to the north. Widths range up to about 12 meters and probably average over 3 meters. Ore shoots are 100 to 300 meters in length, and some are continuous from surface to the present bottom level at about 300 meters depth. The ncrth branch of the vein splits into several sub-branches in the lowermost workings at the west end of the mine. Unmineralized fault gouge and highly siliceous breccia occur in the vein system between the ore shoots.

The average grade of ore at Osor is 45 percent CaF_2, 30 percent SiO_2, 6 percent $CaCO_3$, and small percentages of Zn and Pb and of $BaSO_4$. For 20 years French interests mined the vein for lead, but since 1943, under Spanish ownership, it has produced about 1.5 million tons of fluorspar-lead-zinc ore. Nearly 650,000 tons of acid- and metallurgical-grade spar have been produced from Osor to date, together with 40,000 tons of lead and 60,000 tons of zinc concentrates.

The Torgola deposit in northern Italy is now depleted, or essentially so. Ten to 15 years ago it was the outstanding individual producer in the industry, producing nearly 100,000 tons of acid-, metallurgical-, and ceramic-grade fluorspar annually. The deposit consisted of a number of veins along a fault in a rock of dioritic or grano-dioritic composition. The principal vein had a thickness of 8 to 10 meters and was unusually consistent in width and grade. In 1959, at the time of the last visit by DuPont geologists, it had been worked through a vertical distance of 245 meters, and drilling had indicated another 150 meters of ore below the lowest workings. It almost certainly produced 1 million tons of ore, and probably considerably more than that.

The Muscadroxiu-Genna Tres Montis vein system in Sardinia is particularly notable, and is currently one of the world's largest individual producers. It is reported that it has a continuous strike length of some 3,000 meters and averages

5 to 10 meters in width, with widths up to 18 meters in places. The ore ranges from 50 to 80 percent CaF_2, with barite and relatively high lead values in some places. Proved and blocked out ore reserves along this structure amount to some 6 million tons.

The Longstone Edge-Sallet Hole deposit in Derbyshire, England, is said to be 3½ miles long and has been mined both on the surface and underground. Open-pit widths have ranged mostly between 30 and 40 feet, and depths of 120 to 130 feet have been reached in places. The surface vein material is soft and clayey, and when the property was visited in April 1969, the ore was running 55 percent CaF_2, 11 percent barite, and 1.5 percent lead. In underground exposures the vein is 20 to 30 feet wide. In 1969 this vein system was credited with containing 3 to 4 million tons of ore.

The Rosiclare-Goodhope vein was not quite in the same class as those described previously, but was the richest, most consistently mineralized and productive vein in the Illinois-Kentucky region. At least 800,000 tons of finished fluorspar was taken from it. It occupied a fault having a known length of nearly 2 miles and was worked from the surface to depths of over 700 feet. The maximum width of minable ore encountered was 14 feet and averaged 5 to 6 feet throughout the mine. Throughout very large areas this vein consisted of nearly pure spar from wall to wall, and ore pinches were remarkably small and localized.

The Criciuma fluorspar district of Brazil, located in the state of Santa Catarina, could possibly represent the longest fluorspar structure known to date. Five operating mines are situated along a N. 35° E. fault zone which can be traced along strike for approximately 25 kilometers. The commercial ore bodies occur as discontinuous lenses which pinch and swell both laterally and vertically in a Precambrian quartz monzonite porphyry, and are located where overlying Carboniferous sedimentary rocks have been eroded to expose the basement.

The district is separated into two distinct sectors. The southernmost 10 kilometers is characterized by coarse clean spar averaging 4 to 5 meters in width near the surface and running 70 to 75 percent CaF_2, whereas the most northerly

6 to 7 kilometers contains more silica and clay, resulting in a decrease of grade to ±40 percent CaF_2. Vein width decreases to ±3 meters in the northern sector. Throughout the district, vein width decreases to about 2 meters at the -100-meter level; this thinning with depth is accompanied by an increase in silica content.

The principal vein of the Criciuma district is typically coarsely crystalline spar with chalcedony as the only primary diluent. Reactivation along the northern sector of the fault zone has caused gouge to be supergenetically introduced into the mineralized zone. Mineralization does not penetrate the host rock, nor does the spar contain xenoliths of the quartz monzonite. Contacts are sharp; there is only minor koalinization (5 to 10 cm) along the hanging wall and footwall. Texture-zoning is characteristic throughout the district, with acicular growth near the contacts grading inwardly to saccharoidal agglomeration. This intermediate zone then yields to tranquil last-state subhedral to euhedral textures in the central portion of the vein.

It has been estimated that the Criciuma district has produced 1 to 2 million tons of concentrates of all grades since the beginning of mining.

Several other smaller occurrences in the State of Santa Catarina indicate that the deposition of spar in this part of Brazil is confined to a structurally controlled environment in a lithologically distinct host rock.

Two-thirds of the Spanish fluorspar production comes from fissure veins in the Asturias region of northern Spain, in the area of the Cantabrian Cordillera. The local mining centers are Oviedo, Caravia, and Ribadesella. The veins occur in faults or joints oriented northwest or northeast and having steep dips in both easterly and westerly directions. Widths are about 4 to 6 meters, but one vein, located at Caravia, is 20 meters wide. As a rule the veins are wider at the top and diminish with depth. Lengths are up to about 500 meters. Wall rocks are mostly Carboniferous limestone, but in some places they consist of Permo-Triassic clays and breccias. The shapes of these vein deposits suggest possible karst-type solution cavities along fractures. Ore grades average 25 to 30 percent CaF_2, with 15 to 20 percent $CaCO_3$ and as much as 50 percent SiO_2.

Stratiform deposits in carbonate rocks are also common throughout the world, occurring in Illinois, Italy, Spain, Tunisia, South Africa, and Mexico, for example. These tabular bodies occur in favorable carbonate beds, in many places directly beneath a shale, sandstone, or clay capping, and normally have long dimensions related to some structural feature or features such as joints and faults. The same group of associated minerals occurs in the stratiform deposits as in the vein deposits. In many instances there is some evidence of net loss of volume in the replaced zones with attendant development of gentle synclinal structures in overlying strata or of collapse structures, some of which are pipelike in shape. In some districts, as in southern Illinois, there is no recognizable connection between the mineralization and any igneous activity, whereas at others, such as the Encantada district in northern Coahuila in Mexico, the presence of rhyolite plugs and sills in the general vicinity of the spar deposits, and the direct association of spar with diffuse rhyolite injections along bedding planes, makes one lean toward associating the two.

Stratiform deposits occur in the mountainous region of southeastern Spain known as the Betic Cordillera. The major lead-fluorspar deposits are confined to the smaller mountain chains, called the Alpujarride nappes, which surround the picturesque, snow-capped Sierra Nevada Range between Granada and Almeria. The Triassic formation, which contains the deposits and from which the Phoenicians, Romans, and Moors mined lead, is a carbonate series. The mineralization is specifically related to the dolomitic beds within the series. The beds have been variably folded and faulted.

The lead and fluorspar ore occurs at several horizons forming irregular and lenticular bodies. The bedded deposits have rhythmic banding of fluorite and dolomite similar to the "coon-tail" ore of the Illinois district. Small amounts of sphalerite, cinnabar, and copper oxide occur with the fluorspar. Some parts of the deposit are heavily brecciated while other areas are not disturbed. Thicknesses are on the order of 1 to 2 meters, in some places 4 to 5 meters, and lengths are 0.5 to 1 kilometer. Mining the highly irregular beds is difficult and expensive. Most fluorspar mining

to date is from the waste dumps left by the past civilizations. Grades of lead ore in place range from 1 to 5 percent, and fluorspar ore grades from 10 to 40 percent. Total fluorspar production probably has not exceeded 500,000 tons of acid, metallurgical, and ceramic grades.

On the north coast of Spain in the region west of Ribadesella and east of Oviedo in the Asturias district, bedded deposits occur in the Permo-Triassic section which contains calcareous rocks, sandstone, and conglomerate. These mineralized zones are bounded by clay beds. Thicknesses of mineralized beds range from 2 to 10 meters, and ore bodies can cover areas of 1 square kilometer or more. Grades of ore range from 15 percent to 35 percent CaF_2, with 20 to 30 percent $CaCO_3$ and about 30 percent SiO_2. There are no known igneous intrusives in the fluorspar district of Asturias.

Replacement deposits in carbonate rocks along the contacts with intrusive rhyolite bodies are notably well developed in the Río Verde, San Luis Potosí, and Aguachile districts in Mexico. They include some of the individually largest and highest grade fluorspar deposits known. The fluorspar is not thought to be contact metamorphic in origin. It was probably introduced later, following the contact zone as a conduit and replacing the limestone outward from the contact either massively or selectively along certain beds. At Aguachile cross sections show ore shoots crudely resembling one side of a Christmas tree.

Stockworks and fillings in shear and breccia zones are fairly common in occurrence. Many veins in the western United States are of the stockwork type, and though they may be wide, are usually of low overall CaF_2 content.

Fluorspar is a common mineral in carbonatite and alkalic rock complexes, and is sufficiently abundant in some to comprise economic or potentially economic deposits. The Okorusu deposit in South West Africa is the best known of this type of occurrence. This deposit consists of a number of bodies of fluorspar in a 900-foot-high curving ridge made up of limestones, quartzites, and related rocks which have been intruded and metamorphosed by an alkalic igneous rock complex, including a nepheline syenite stock. The fluorspar appears to have replaced bedded and brecciated limestone, marble, and quartzite, forming large lenticular masses of irregular shape. Apatite and quartz are abundant accessory minerals. Some consider the fluorspar to be a manifestation of contact metamorphism of the sedimentary rocks by the nepheline syenite, but this is debatable.

A number of years ago concentrations of fluorspar in the clayey and sandy residuum left by the surficial weathering of fluorspar veins were significant sources of metallurgical fluorspar in Kentucky and Illinois. There is a little of this material still being worked, but not much. Log washers and jigs were the principal concentrating machinery. Currently a significant amount of fluorspar is still being recovered from this type of deposit in the Asturias district of northwestern Spain, but most of the product is being processed into acid-grade concentrate for export.

"Gangue mineral occurrences" may seem to be an odd category for a group of fluorspar sources, but it seems applicable and suitable in a pragmatic treatment of the subject. This covers the production of acid-grade concentrate from lead-zinc mine tailings by Minera Frisco in Mexico, for example, and the similarly large production from old lead mine dumps near Berja in southern Spain by Minersa, which has already been mentioned. In each case, fluorspar occurs as a principal gangue mineral in base metal deposits, and is abundant enough (averaging 10 to 20 percent CaF_2) to be economically recoverable now.

Breccia pipes with fluorspar fillings occur in the Thomas Range in Utah, and elsewhere. These are large enough to have been important producers of metallurgical-grade spar.

Of historical, but presently noncommercial, interest are the occurrences of fluorspar in the gold-telluride pipe complex at Cripple Creek, Colorado, and in a central breccia pipe or breccia zone at Hicks Dome in southern Illinois.

In the classification of replacements of massive inclusions in granitic rocks, the Buffalo and related deposits owned by General Mining in South Africa are outstanding examples. At the Buffalo deposit, fluorspar occurs in the form of abundant parallel veinlets in a large body of fine-grained pink granite enclosed in coarse red granite which is part of the Bushveld complex. Apparently the fluoritized fine-grained granite is the metamor-

phosed remnant of a block of banded sedimentary rock, perhaps a quartzite which had been caught up in the coarse granite. The spar veinlets occur principally along what may have been former bedding planes and, to a lesser extent, in steeply dipping joints. The result is a system of veinlets ⅛ inch to 5 inches thick which contain enough fluorspar to give the deposit an overall content of 20 to 22 percent CaF_2. Monazite and apatite are accessory minerals.

The Crystal Mountain deposits in Montana are another odd occurrence. Large bodies of massive pure fluorspar containing biotite mica, feldspar, quartz, and other igneous rock minerals are embedded in granite and biotite gneiss. They are thought to be of pegmatitic origin, both from their manner of occurrence and from the variety and kind of minerals present. They have been a major source of metallurgical-grade spar.

Deposition of fluorspar in open cavities is a relatively rare occurrence. A spectacular deposit of this type is in the San Vicente district of Coahuila, on the west side of the Boquillas valley, roughly 60 miles south of the village of Boquillas. Fluorspar occurs in both veins and mantos in limestone as very pure massive incrustations which often have spectacular mamillary and stalactitic and stalagmitic structures. There is no doubt that here the fluorspar was deposited in open cavities.

Another place where fluorspar was deposited in open spaces is the Fluorspar-Gero-Penber vein system on the Northgate property of Ozark-Mahoning in Colorado. Here fluorspar occurs in botryoidal layers on the walls of open fissures and as concretionary masses surrounding fragments of country rock. The lower parts of many of the still-open areas of the fissures are partly filled with these concretionary pebble-like masses, which are in places cemented together into porous, rubbly aggregates. In one place a stalactitic growth was observed. The core of this growth was finely crystalline white quartz having a central tubular opening like regular calcitic stalactites. The growth was covered with layered fluorite.

Fluorspar occurs in clayey and sandy pyroclastic sediments in the beds of several former lakes in the Castel Giuliano area about 25 miles north of Rome, Italy. One, probably the largest of the group, which has received much attention in the press, is the Soricom deposit. Apparently gases or solutions of volcanic origin permeated the lake sediments, resulting in the deposition of very minute disseminated crystals of fluorspar. Fluorspar makes up 50 to 60 percent of clayey parts and about 15 percent of the sandy parts of the deposits, and is accompanied by barite, apatite, and gypsum. Apparently there are millions of tons of fluorspar in these deposits, but the exceedingly fine grain size of the crystals has proved a real block to developing them. The Soricom deposit alone is credited with 8 million tons of material in a bed 1.65 meters thick.

We have briefly considered 12 different types of depositional environments for fluorspar. Fissure veins and stratiform deposits are by far the most important, at least from the commercial standpoint, but the point is that there is no characteristic, single, geological mode of occurrence for fluorspar. Similarly, fluorspar may be epigenetic, and evidently usually is, or it may appear to be syngenetic. It may be impossible to frame a characteristic depositional environment for fluorspar except by using the parameters of chemistry and physics: the composition of the ore-forming agents and the temperature and pressure operative in the zone of deposition.

GEOLOGY OF THE DERBYSHIRE
FLUORSPAR DEPOSITS, UNITED KINGDOM

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ABSTRACT

An account is provided of the nature and origin of fluorspar mineralization in the South Pennine orefield where deposits are located on the eastern flank of the Derbyshire dome and restricted stratigraphically to Visean limestones of the Carboniferous System in a structurally controlled environment. The main deposits are of fissure-vein type but fluoritization of limestone in fractured or well-jointed zones has given rise to replacement deposits especially in the vicinity of impervious volcanic rocks and Namurian shales. The existence of fluorite infillings associated with cave deposits provides another facet of what is shown to be a polyphase mineralization which commenced in the early Permian, after the Hercynian orogeny, and possibly extended through to the Triassic Period. Extensive erosion and peneplanation of the Carboniferous strata was taking place at this time, and its effects together with those of subsequent geological events on the mineralization history of the area are considered. Current views on the origin of the ore-forming fluids are examined, and a juvenile source for the elements Pb, Zn, F, and Ba possibly mixed with connate brines is favoured. The juvenile fluids are thought to have emanated from a magmatic source which was also responsible for the increase in geothermal gradient necessary to promote hydrothermal activity.

INTRODUCTION

Fluorspar occurrences in the United Kingdom are quite numerous and distributed over a wide area extending from the northeast of Scotland, where they occur as narrow veinlets and disseminations in the Helmsdale granite and adjacent Devonian arkoses (Gallagher and others, 1971), to the southwest of England where fluorspar is an important gangue mineral associated with old lead mines in the Tamar Valley (Dunham, 1952b). Major fluorspar deposits of economic significance are restricted to the North and South Pennines where they occur in limestones and associated sediments of Lower Carboniferous age.

The present paper is concerned exclusively with fluorspar in the South Pennine orefield which lies within the county of Derbyshire and covers an area of approximately 200 square miles. Here the Carboniferous Limestone Series, the oldest rocks exposed in the area, occupy the centre of a complex dome-like structure flanked by progressively younger strata of the Carboniferous System on three sides and unconformable Triassic sediments to the south.

It is an upland region of outstanding natural beauty, generally 800 feet or more above sea level, and one of contrasting scenery where rolling limestone pastures give way to open moorland and precipitous gritstone crags rising to over 1,500 feet. The hills are separated by often deeply incised river valleys, particularly the Derwent, Wye, Dove, and Manifold which flow into the River Trent at the southern end of the county (Fig. 1). The northern part of Derbyshire is in fact referred to as the Peak District and lies within the Peak District National Park.

PREVIOUS WORK

The first detailed geological account relating specifically to fluorspar in Derbyshire was given by Wedd and Drabble (1908). The Geological Survey memoir on fluorspar by Dunham (1952b)
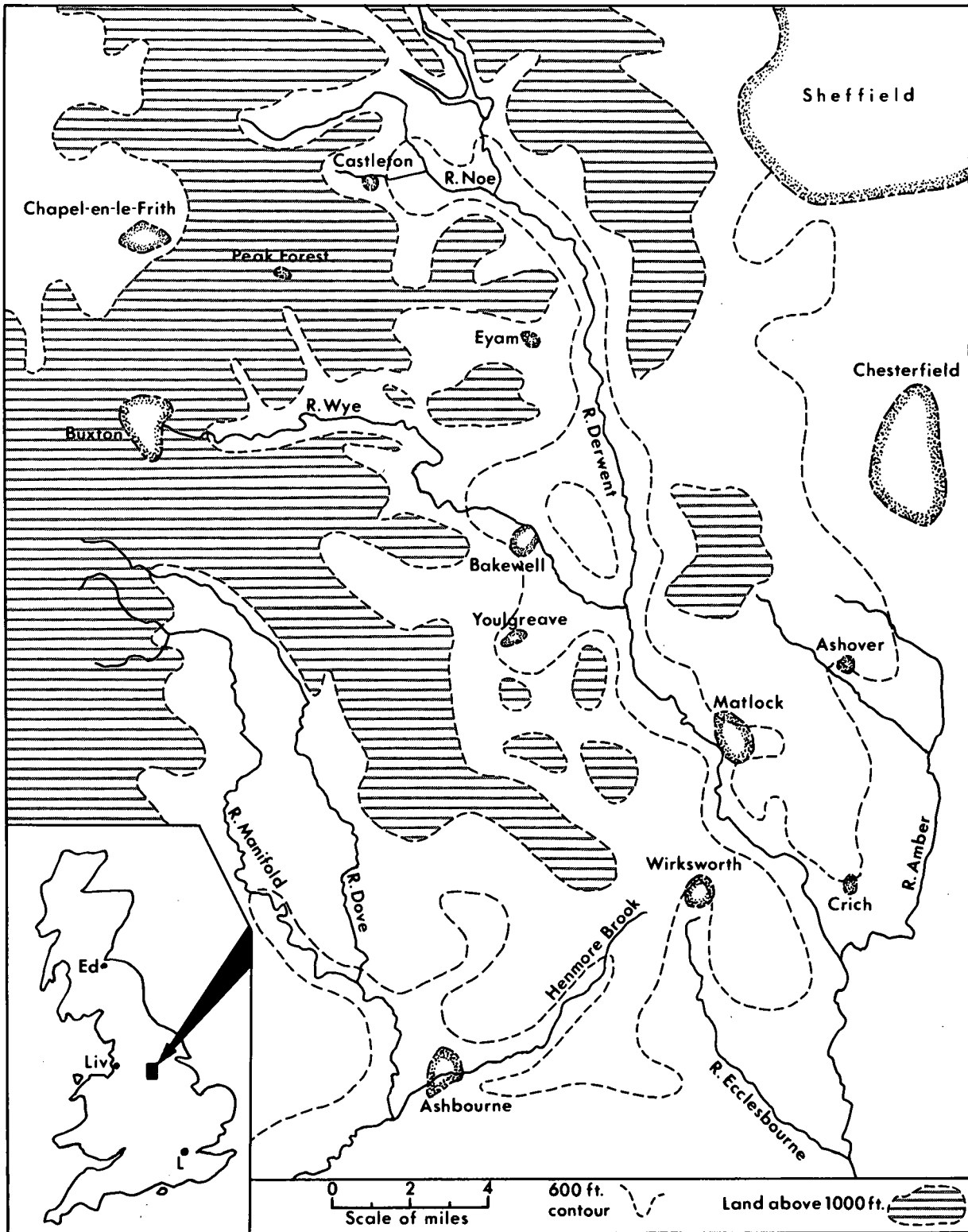
Figure 1.   Location map and physical features.

is a more recent account of the Derbyshire occurrences, but the most up-to-date paper is by Ford and Ineson (1971) on the fluorspar mining potential of Derbyshire. It provides a detailed description of individual veins and properties, a general account of the stratigraphy, structure, and mineralization of the district, information about the old lead-mining laws and customs, and a comprehensive list of references. There are two recent 1 inch to 1 mile Geological Survey maps and related memoirs which provide detailed geological accounts of the north and southeast parts of the orefield (Stevenson and Gaunt, 1971; Smith and others, 1967).

The present paper does not aim to add significantly to the amount which has already been written on the nature and origin of mineral deposits in Derbyshire. It has been prepared specifically for this symposium and to a certain extent reflects the views of the author which have developed over the past 4 years while being concerned with the exploration and mining of fluorspar.

GEOLOGICAL FRAMEWORK

Stratigraphy

Mineral deposits in Derbyshire are associated with the highest member of the Carboniferous Limestone Series (Visean); the overlying Millstone Grit Series (Namurian) and Lower Coal Measures (Westphalian) are rarely mineralized.

Carboniferous Limestone Series

The Visean rocks exposed in the area are essentially limestones with interbedded chert and contemporaneous volcanic rocks, known locally as toadstones. They attain a maximum exposed thickness of approximately 1,500 feet, but a recent borehole sunk by the Institute of Geological Sciences near Eyam has intersected at least 5,900 feet of Carboniferous strata resting unconformably upon Ordovician mudstone (Dunham, 1973). The lowest Visean and underlying Tournaisian rocks include dolomites and anhydrite bands interbedded with mudstones.

The detailed stratigraphy is complicated by the paleogeographic conditions under which the rocks were deposited. This part of the country acted as a stable block during the deposition of the Visean sediments giving way northwards in the vicinity

of Castleton to an area of subsidence and a corresponding change of facies from pale massive limestone with a coral-brachiopod fauna to thinly bedded limestones and shales with a goniatite-lamellibranch fauna. The marginal zone between the shelf and basin facies in characterized by the presence of extensive coral reefs. This reef belt is well developed on the western and southern edges of the block near Buxton and Brassington.

A wide range of lithological types has resulted from these varying conditions of sedimentation, and bioclastic limestones containing brachiopod and crinoid debris in well-defined bands can be contrasted with pale massive limestones and dark bituminous limestones. Chert is well developed at certain horizons and occurs either as discrete nodules or layers up to 1 foot thick interbedded with the limestone.

Contemporaneous volcanic rocks are common throughout the area where they form a series of impervious layers within the limestone succession. Unfortunately, rapid lateral variations in thickness and lack of continuity make it difficult to correlate individual volcanic horizons across the orefield. Two composite stratigraphic columns are provided to indicate the limestone subdivisions found in the north and south of the area together with the more important volcanic units (Fig. 2).

The volcanic rocks include lavas, tuffs, and agglomerates. Typical lavas are grey-green olivine basalts with calcite- and chlorite-filled amygdales when fresh, but many have suffered secondary alteration through chloritization and carbonation. They are usually underlain and overlain by green to ochreous volcanic clays. Individual lava flows attain thickness of up to 250 feet in the north of the area but rapid lateral variations are common. The Upper Miller's Dale Lava, for example, decreases in thickness from 60 feet to 8 feet over a distance of 400 yards (Stevenson and Gaunt, 1971). Similar variations are seen near Masson Hill where the Matlock Lower Lava and Matlock Upper Lava are 380 feet and 120 feet thick, respectively, and thin rapidly when traced southwards. The greatest volcanic pile occurs further east in the vicinity of Ashover where over 900 feet of lavas and tuffs, broken by two thin limestone units, suggest close proximity to a volcanic centre.
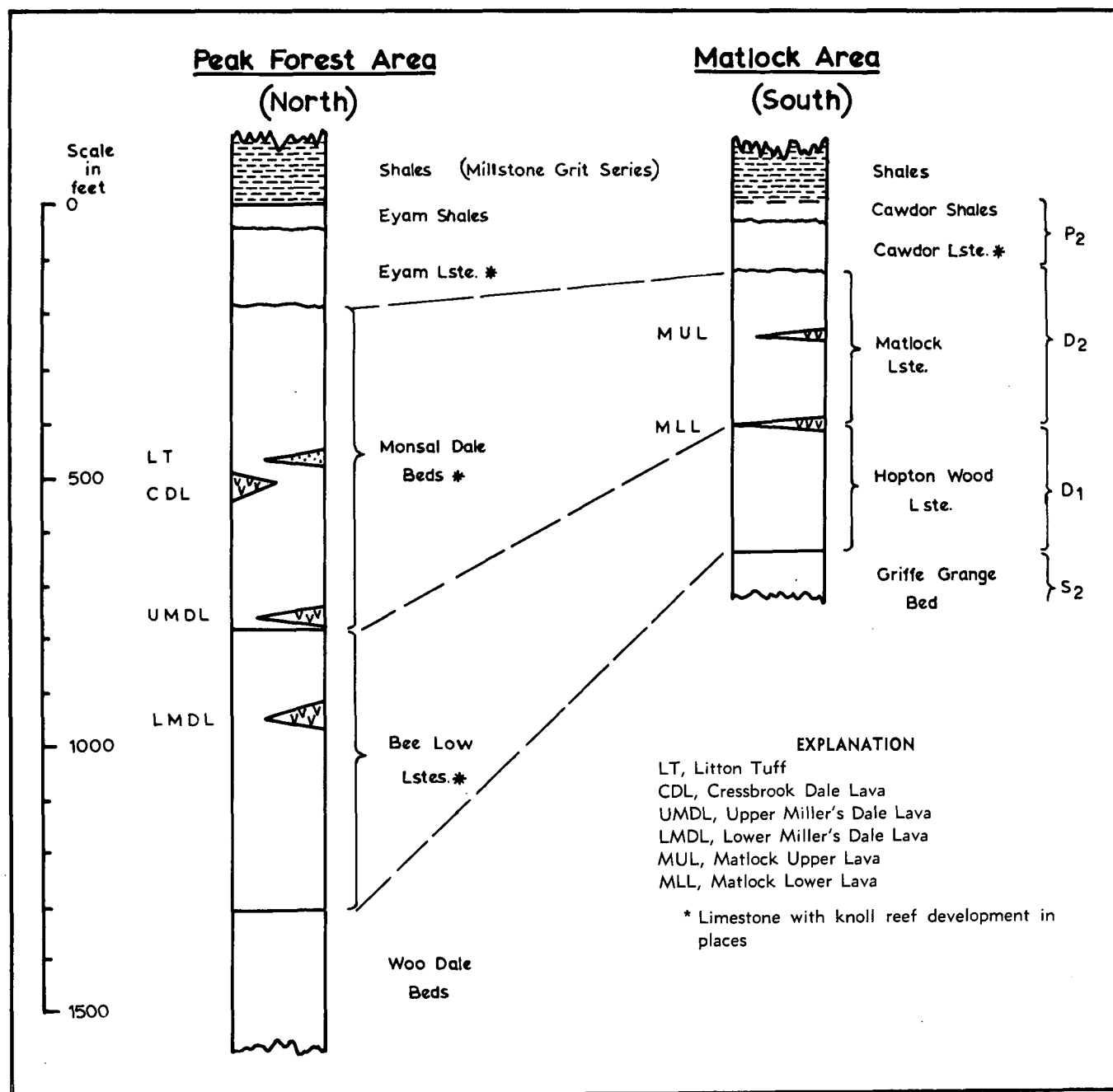
Figure 2. Composite sections of the Carboniferous Limestone Series.

Bedded pyroclastic rocks vary from 100-foot-thick units down to thin clay wayboards of less than 1 foot. They are grey-green, calcitized, variably textured rocks which frequently exhibit repeated gradational changes from coarse lapilli tuffs to fine volcanic clays. Lateral variations in thickness are common and are thought to be partly due to contemporaneous erosion.

Volcanic vents occur at a number of localities including Bonsall Moor and Grangemill west of Matlock and Monksdale in the north of the area. They are composed of coarse agglomerates and lapilli tuffs with limestone and volcanic fragments embedded in a greenish matrix.

Contemporaneous intrusive igneous rocks of similar composition are olivine dolerite sills.

There are five in the north of the area, of which the Peak Forest sill is the largest, and two in the south at Bonsall and Ible. Age determinations on one of the northern sills, using the K-Ar method, gave an average age of 311±6 m.y. which puts the intrusive episode at about the Namurian-Westphalian boundary (Stevenson and others, 1970).

Millstone Grit Series

The limestones are overlain unconformably by an alternating series of shales, sandstones, and gritstones which are approximately 1,300 feet thick in the south and southeast of the area, increasing to over 4,000 feet in the north and northwest (Fig. 3). The lowest member of the Millstone Grit succession is a 500- to 800-foot-thick, impervious formation of dark-grey pyritous marine mudstones and shales with thin limestone and siltstone bands.

Structure

The main structural features of the area are the product of the Hercynian earth movements which took place at the end of the Carboniferous Period, but the main limestone block and surrounding basinal areas were in the process of development from Visean times onwards. The present limestone outcrop represents the broad axial region of the so-called Derbyshire dome. It is an area of gently undulating strata with a number of well-defined fold structures flanked to the east and west by much stronger folding on a general north-south axis (Fig. 3).

The dominant structure in the northern part of the limestone outcrop is the Peak Forest anticline, a north-northwest-trending fold with a gentle plunge to the north and south, but on the eastern flank of the dome the major fold axes trend east-west. Here the easterly plunging Abney, Chatsworth, and Stanton synclines are occupied by Millstone Grit Series rocks. A major anticlinal structure with a similar trend in the northern part of the area is the Longstone Edge monocline which has a steeply dipping southern limb; the Matlock anticline is an important easterly plunging fold in the limestones further south.

A contrasting structure to the east of the dome is the tight, sinuous, northerly to northwesterly trending anticline which provides a link between the two limestone inliers of Crich and Ashover and can be traced further north in the overlying Millstone Grit. Fold axes with a similar trend are present on the western flank of the dome.

The fold structures are accompanied by extensive faulting and jointing. The dominant fault trend throughout the area is easterly to east-northeasterly, and this is accompanied by a set of west-northwesterly to northwesterly faults. The latter are of importance southwest of Matlock where the Bonsall and Gulf faults have throws of over 400 feet in places, and a graben is developed between the two.

Many of these faults and joints with a similar trend are mineralized. Initially the majority were normal faults with a measurable vertical displacement, but the presence of brecciated vein material with horizontally slickensided surfaces indicates that post-mineralization wrench faulting has taken place along many of them.

Post-Hercynian Evolution of the District

The geological history of the area after the Hercynian orogeny was one of almost continuous uplift and erosion accompanied by periodic earth movements along existing planes of weakness. The initial uplift of the Pennine massif led to the removal of several thousand feet of Upper Carboniferous strata so that by late Permian times peneplanation had progressed sufficiently to allow ingress of marine conditions from the east. Solutions derived from this Zechstein sea are thought by Dunham (1952a) to have been responsible for the dolomitization of the Carboniferous Limestones prior to mineralization. Unfortunately there are no Permian deposits preserved in the area to support this view nor remnants of later Mesozoic and Tertiary rocks with the exception of so-called pocket deposits of clays, silica sands, and gravels which represent late Tertiary infilling of collapsed cave systems developed in the limestone.

Evolution of the present land surface can be traced back to Tertiary times, but it is reasonable to assume that cavernization of the limestone commenced much earlier than this. Pre-mineralization cavernization is present in the area, but most of the orebodies provide evidence of ex-
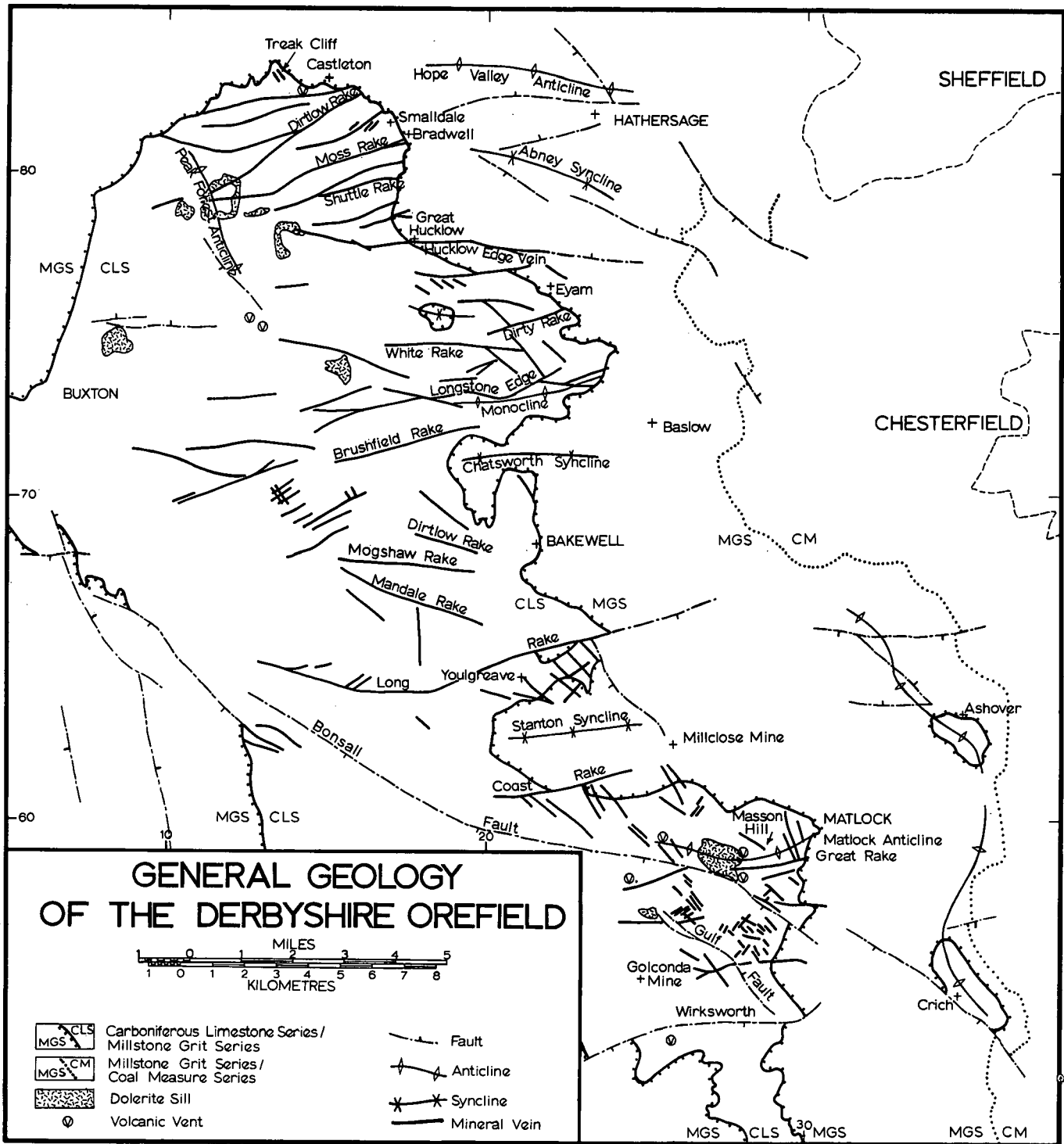
Figure 3. General geology of the Derbyshire orefield.

tensive post-mineralization solution and erosion. Solution features ranging from narrow gullies and water channels to cathedral-like cave systems are common, and the majority of these exhibit depositional features as well. These include the

development of calcite crystals in vugs and on the surface of limestone boulders and transported mineral-bearing sediment backfill, both of which reflect variations in ground-water level and rates of flow.

MINERALIZATION

General Features

The mineralization is restricted from a stratigraphic viewpoint to the Carboniferous Limestone Series, although there are rare examples where it extends into the overlying Millstone Grit and Coal Measures (Stevenson and Gaunt, 1971). The location of mineralization within the limestone is largely controlled by the fracture pattern resulting from the Hercynian earth movements. This has given rise to vein-type deposits which follow the main lines of structural weakness and are known locally as rakes.

The more important vein systems such as Hucklow Edge, Longstone Edge, Long Rake, Coast Rake, and Great Rake all exhibit a general east-west trend and extend for several miles (Fig. 3). They appear to be located on or near the crests of structural highs, and in this respect the Longstone Edge vein system is unique because of its association with a major monoclinal structure. Where these veins are traced in an easterly direction they disappear beneath the shale-gritstone cover but do not extend upwards into it.

Smaller veins and joint infillings, rarely exceeding 2 feet in width, have been called scrins by the old lead miners. Also the terms flat and pipe have been used to describe tabular and elongate replacement orebodies which have developed selectively parallel to the bedding and along enlarged joint systems, respectively.

The main minerals contained in these veins and other deposits are fluorite, baryte, calcite, quartz, and galena. Other sulphides including sphalerite, pyrite, and chalcopyrite are present in the area but are limited in their abundance and distribution. The relative proportion of the main gangue minerals varies across the orefield, but as a general rule the fluorite content of the main veins decreases from east to west. There are a large number of additional minerals known to occur in the orefield, and a list has been compiled by Ford and Sarjeant (1964) in their mineral index of the Peak District.

Host Rock Alteration

Secondary alteration of the limestone country rock has taken place in well-defined areas either prior to or as part of the mineralization. Dolomitization, silicification, and fluoritization are the processes involved but the latter will be described elsewhere.

The effects of dolomitization can be seen in the south of the orefield near Brassington and Wirksworth and also in the Bonsall Moor-Masson Hill area where dolomitized limestone can be traced in a general west-northwesterly direction for a distance of 10 miles. Dolomitization in this area appears to be a near-surface phenomenon and transgresses bedding planes. The contact between dolomite and underlying limestone is sharp. In some areas an interfingering between the two can be seen and occasionally lenses of dolomite are developed in the limestone (Smith and others, 1967).

Dolomitized limestones in the north of the area are not common. They are located approximately 35 feet above the dolerite sill at Peak Forest in an area where the limestones immediately above the intrusion are marmorized and accompanied by the development of secondary nodules of silica (Stevenson and Gaunt, 1971).

Silicification of limestones is usually restricted to the wall rocks adjacent to mineral veins and therefore could be considered as part of the mineralization process, but more extensive silicification has taken place in the Bonsall Moor area where it can be traced for a distance of $2\frac{1}{2}$ miles along the axial region of the Matlock anticline, in addition to the walls of major veins such as Great Rake.

The boundary between fissure veins and limestone wall rock is in many cases clear cut with no visible signs of alteration attributable to the mineralization process. Ineson (1969, 1970), in his study of wall rocks in Derbyshire found evidence of calcite recrystallization, impregnation with quartz, and dolomitization in some instances. The dispersion of some trace elements showed a logarithmic decay pattern with increase in distance from the vein to form distinct aureoles. The Hucklow Edge vein exhibited a 35-foot-wide Zr and F aureole, with Pb and Zn not quite attaining this width. Dispersions were more erratic in areas where micro-fractures had allowed extensive migration into the wall rocks. Two common features were the decrease in Sr adjacent to the veins, said to be due to the dissociation on

recrystallization of calcite in the wall rock, and the increase in Zr which was considered to reflect a magmatic source for the ore-forming fluids.

Type of Deposit

The fluorspar deposits have been divided into three main groups for descriptive purposes: vein deposits, replacement deposits, and cave deposits, but in actual fact all three are interrelated.

Vein Deposits

Vein deposits may be either simple or complex. Simple vein deposits are narrow joint and fissure fillings from less than 1 inch up to 2 feet in thickness. They frequently exhibit a zonal arrangement of minerals with crystalline fluorite margins, a baryte wall zone, and fluorite-baryte-calcite-galena core. The dominance of one constituent over another varies from one part of the orefield to another, but the most abundant mineral is either calcite or baryte. Extensive areas of Bonsall Moor are criss-crossed by large numbers of northwest- and northeast-trending scrins of this type, but further south near Cromford narrow fracture fillings cutting dolomitized limestone are composed mainly of fluorite.

The major veins, or rakes, are vertical to near-vertical complex fissure veins. They range in width from 1 foot to 30 feet or more, and individual veins can vary by these amounts in a lateral and vertical sense. Many become attenuated or appear to pinch out altogether where they are in contact with volcanic rocks, but in most cases narrow fluorite-filled fractures indicate that channelways were present during mineralization, thus allowing the passage of mineralizing solutions to more favourable environments of deposition. However, there are examples such as White Rake near Tideswell and Great Rake near Matlock where widths of veins are hardly diminished where they cut across the volcanic units.

Although the mineral distribution in the larger veins is extremely complex, some exhibit a simple zonal arrangement near the vein walls. High Rake on Longstone Edge, for example, in one area has an outer 1-inch marginal zone of colourless crystalline fluorite with specks of galena, followed by a 1-foot wall zone of pale-brown, fine-grained colloform baryte studded with small grains of galena aligned parallel to the banding,

and a 6-foot wide complex core of admixed fluorite, baryte, and galena. Here irregularly orientated blocks of colloform baryte are embedded in a coarsely crystalline matrix of fluorite which also penetrates the baryte wall zone as narrow veinlets indicating a polyphase mineralization.

Barytic wall zones are not always developed. The eastern end of Hucklow Edge vein, for example, is composed of crystalline aggregates of colourless fluorite with small amounts of intergrown baryte, calcite, and galena. Fluorite-rich veins in the Ashover area also fail to show any marked zonal arrangement. On Shuttle Rake near Bradwell impersistent remants of fluorite, calcite, and baryte wall-zone mineralization up to 1 foot in width are dominated by a 6-foot-wide core of successive white calcite crustifications, a characteristic feature of the veins in this area.

In addition to the contemporaneous earth movements and related phases of mineralization to account for the disorderly arrangement of the vein fill, there is ample evidence of post-mineralization faulting which has resulted in cataclastic deformation of the veins. Brecciated and pulverized, almost mylonitic, fluorite with streaks of galena and baryte is a common feature on the Hucklow Edge vein, for example.

Replacements Deposits

The term replacement is used here in its literal sense for deposits which have developed at the expense of a host rock. They are composed essentially of pale-brown, fine-grained, crystalline aggregates of massive fluorite with occasional crystal-lined vugs, but in more advanced stages of replacement more coarsely crystalline fluorite may be present together with varying amounts of baryte and galena comprising a typical vein assemblage.

Unaltered chert nodules are a common feature of many replacement bodies, but usually their high silica content is due to the presence of microcrystalline quartz-fluorite intergrowths whose interrelationships indicate that silicification of the host rock preceded fluoritization.

All known replacement deposits in Derbyshire have developed in areas where there is some structural control to the mineralization. It is not surprising, therefore, to find replacement deposits

adjacent to major fissure veins where wall rocks are extensively brecciated. Stratigraphic controls are important as well, and the most favourable area for fluorspar replacement deposits to be found is directly above an impervious volcanic unit and, less frequently, beneath the impervious shale cover. One of the best examples is the replacement deposit associated with the Long Rake fissure vein at Raper mine near Alport described by Ineson and Al-Kufaishi (1970). They established a paragenetic sequence based on field mapping and a study of polished sections which indicated three generations of baryte and five generations of fluorite. Replacement of the limestones adjacent to the fissure vein over a width of at least 150 feet was related to the youngest episode of fluoritization and probably preceded by partial dolomitization and silicification.

Ineson and Al-Kufaishi (1970) postulated that the limestone replacement was directly related to the presence of a shale caprock which overlies the limestone on the south side of Long Rake. Deep opencast operations subsequent to their work have added confirmation to this view, but in addition it is clear that a volcanic zone approximately 120 feet beneath the shale cover in an area of complex faulting has also played its part in controlling the location of the replacement body.

The Masson Hill replacement described by Dunham (1952b) is one of the better known fluorspar flats in Derbyshire. It lies above the Matlock Lower Lava where limestones have been replaced over a maximum proved width of nearly 800 feet to a general height of 18 feet and as high as 50 feet along some joints. The deposit appears to have developed from the mineralization of a belt of northwest-trending scrins and a conjugate set more or less at right angles cutting dolomitized limestone. Similar replacement deposits overlie the Matlock Lower Lava at Jugholes Wood 0.5 mile northwest of Masson Hill and more or less on the same line of strike.

Cave Deposits

Derbyshire like most limestone areas is noted for its natural caverns which owe their origin to solution along preferential lines of weakness such as joints, fault planes, and the more susceptible lithologic units. There is evidence to suggest that some of the orebodies were formed in areas where solution and cavernization of limestone preceded mineral deposition. The Golconda mine baryte deposit (Ford and King, 1965) and one of the orebodies at the famous Mill Close lead mine (Traill, 1939) are two well-documented examples.

Fluorspar deposits of this type are common in the north of the area in close proximity to the limestone-shale contact. Ford (1955) has described the fluorite-rich pipe deposits at Treak Cliff near Castleton where mid-Carboniferous caves and sinkholes filled with limestone boulders contain pockets and vugs of the purple banded variety of fluorite known locally as "Blue John." Even the cavities between the boulders are lined with Blue John and some pockets are up to 4 feet across. Similar cave deposits have been intersected by underground workings at Ladywash mine, approximately 150 feet beneath the shale cover. Here a 100-foot by 30-foot northwest-trending, boulder-strewn, 20-foot-high cavern is partly lined with fluorite and calcite crystals, and the walls are cut in places by narrow fluorite-baryte-galena joint infillings and bedding-plane flats up to 6 inches in width. The outer surfaces of some of the boulders are decomposed, and shell-like crustifications of baryte and fluorite are developed around them, together with crystal aggregates of twinned calcite scalenohedra. In addition, there are deposits of transported fluorite-baryte-calcite sand infilling other parts of the cave floor. Post-mineralization supergene effects, probably including an enlargement of the cavernous area, have made it difficult to reconstruct the development of these deposits, but pre-cavernization and post-cavernization mineralization are suspected.

A well-exposed west-northwest pipe development can also be seen in Smalldale near Bradwell where fissured joint surfaces and bedding planes are occupied by radial intergrowths of coarsely crystalline, colourless to pale-mauve fluorite up to 2 feet in diameter, accompanied by some galena and baryte. These flattened, pillow-shaped, interconnecting structures are thought to represent solution channels developed in the limestone prior to mineralization and then subsequently infilled.

Distribution of Fluorspar in the Orefield

As long also as 1908, Wedd and Drabble indicated that workable deposits of fluorspar were restricted to the eastern margin of the orefield and also in the limestone inliers further east of Crich and Ashover. Westwards the vein mineralization became progressively richer in baryte and calcite at the expense of the fluorspar. They produced a map with a line showing the approximate western limit of workable fluorspar deposits which was revised in 1952 by Dunham (1952b) based on more up to date information. It was also stated that this mineral zoning was confused in places where extensive alteration of the limestone had occurred.

In 1954, Mueller departed from the commercial concept of mineral zoning by attempting to show from a study of the composition of the master veins, and the variety of fluorite developed in them, that thermal zones could be demonstrated in the area. He delineated the individual north-south trending zones based on the following data obtained from old records and the sampling of available exposures.

	Percent						
	CaF$_2$	BaSO$_4$	CaCO$_3$	Pbs	ZnS	CuFeS	FeS$_2$
Fluoritic Zone	10-50	2-10	40-85	1-5	½-3	0-10	0-5
Baritic Zone	1-10	10-40	55-85	½-3	0-1	—	—
Calcitic Zone	0-1	0-10	80-99	0-3	0-½	—	—

(*After* G. Mueller)

Fluorite in the fluoritic zone along the eastern margin of the orefield was a colourless variety with inclusions of pyrite and chalcopyrite. Westwards this gave way to a second colourless but turbid variety extended as far as the western limit of his fluoritic zone. Fluorite in the adjacent barytic zone was found to be purple, and it maintained this characteristic across to the central area of the limestone plateau.

Mueller considered that coloured fluorites formed at lower temperatures than the colourless varieties and their association with the barytic and calcitic zones supported the thermal-zone concept. Also, the higher temperature fluoritic zone was located nearer the source of the mineralizing fluids to the east of the orefield.

Subsequent discovery of fluorspar deposits outside the zone boundary and problems over the distribution of coloured varieties of fluorite indicate that although there is a general tendency for the fluorspar content of major veins to decrease from east to west with a corresponding increase in the other gangue minerals, there are sufficient exceptions to warrant a reappraisal of the zonal concept, a task which has already been started by Firman and Bagshaw (1973).

Age of Mineralization

Stevenson and others (1970) have stated that the youngest rocks in the district cut by mineral veins are of Lower Coal Measures age. The mineralization is also later than the intrusive dolerite sills, one of which gave a whole rock K-Ar age of 311 ± 6 m.y. (post-Millstone Grit and pre-Coal Measures).

Determinations by Moorbath (1962) on galenas from the Matlock district giving a mean model age of 180 ± 40 m.y. suggested a Triassic age for the mineralization, but doubts have been cast on the validity of these results by Mitchell and Krouse (1971). They recalculated Moorbath's data for comparative purposes and concluded that the Pennine mineralization took place from late Carboniferous to early Permian (280 m.y. ago). Fitch and Miller (1964) have also suggested that the primary mineralization was associated with the Hercynian orogeny which took place at this time.

Ineson and Mitchell (1973) published data based on samples of highly altered basic lavas and pumice tuffs from areas adjacent to mineralization. Age determinations were carried out on clay-mineral concentrates using the K-Ar method. The results suggested that the clay minerals had been affected by repeated hydrothermal alteration which reflected at least two episodes of mineralization, one at 270 m.y. (early Permian) and the other at 235 m.y. (late Permian). Some dates as recent at 180 m.y. indicated the continuation of hydrothermal events up into the late Trias.

Nature and Origin of the Mineralizing Solutions

Fluid inclusion studies on fluorite by Roedder (1967) indicate a range of filling temperatures from 140°C to 60°C which means that the mineralizing solutions must have entered the areas of deposition at higher temperatures. The salinity of these fluids varies from 18 to 30 percent by weight of NaCl in primary inclusions from Masson Hill, Bradwell Moor, and Treak Cliff, down to between 1 and 3 percent by weight for other pri-

mary inclusions at Treak Cliff. Published data on Na/K ratios have not been found for the Derbyshire fluorites, but it is understood that current workers are finding slightly higher values than the North Pennine fluorites which Sawkins (1966a) puts at 6.8 to 12.4.

Possible sources for these mineral-bearing brines include connate waters trapped and buried with sedimentary formations (fossil sea water), the solution of evaporite deposits by circulating ground water, and finally juvenile fluids of deep-seated origin.

Exploratory drilling for oil has proved the existence of saline ground water in the Carboniferous Limestone, Millstone Grit, and Coal Measures occurring below the Mesozoic rocks of the East Midlands. Analytical results of ground-water samples from the Carboniferous Limestone have been studied by Downing (1967) who found that the concentration of dissolved solids increased in an east-northeasterly direction away from the Derbyshire dome up to a maximum of 100,000 ppm. This increase in salinity was accompanied by a change in composition from bicarbonate to sulphate and finally chloride. Downing concluded that these brines were connate waters—fossil Carboniferous Limestone and Millstone Grit sea water—diluted by meteoric water which had moved downdip from west to east from post-Cretaceous times onwards. It is possible that similar connate brines undiluted by meteoric water could have existed in the Derbyshire limestone at the time of mineralization, but their ability to provide adequate concentrations of Pb, Zn, F, and Ba is doubted.

Other sources have been suggested for the Derbyshire mineral-bearing brines. Davidson (1966) favoured the leaching of overlying Permian evaporites by circulating ground water. The main objections to this view include the lack of evidence to substantiate the former existence of evaporite deposits in the area, the fact that known Permian evaporites have a low metals concentration, and finally one of timing. Since the primary mineralization is considered to be post-Carboniferous to early Permian in age, ground-water brines from a Zechstein source could only have been of significance in the later phases of hydrothermal activity in the area.

The discovery of Lower Carboniferous evaporites at depth in the orefield offers an attractive alternative which could gain support if brines with a high metal content were proved to have existed in the area. Unfortunately, ground-water studies so far have shown that this is not the case, and the only acceptable source for the mineralizing elements Pb, Zn, F, and Ba would appear to be a juvenile one. It is acknowledged that these juvenile fluids could have blended with connate brines to form the mineralizing solutions, and it is possible that sulphate ions may have been leached out of the Lower Carboniferous evaporites.

ORIGIN OF THE MINERALIZATION

When Wedd and Drabble (1908) came to account for the origin of the fluorspar mineralization, they listed facts and observations which had some bearing on the question and then suggested the most reasonable hypothesis to fit them. A similar procedure is adopted in the present paper.

1. Age determinations indicate that the mineralization history spanned at least 100 million years with the first major hydrothermal event taking place towards the end of the Hercynian orogeny. Field and laboratory studies support this Permo-Triassic polyphase mineralization.

2. Stratigraphically the known mineral deposits are restricted to the upper part of the Carboniferous Limestone Series; occurrences in the overlying Millstone Grit and Coal Measures are rare. Recent borehole evidence near Eyam has proved that the mineralization is underlain by over 5,000 feet of Lower Carboniferous strata with dolomite and anhydrite occurring near the base of the succession.

3. The greatest accumulation of contemporaneous volcanic rocks is located on the eastern flank of the orefield near Ashover, but numerous volcanic vents together with late Carboniferous dolerite sills indicate a high-level penetration of the main limestone block by intrusive igneous rocks and the existence of more than one emanative centre.

4. The mineralization is restricted in its location to joints and fissure systems in the

limestone or their immediate vicinity where local depositional factors, in addition to structural controls, have enabled more extensive areas to be mineralized, resulting in the formation of replacement pipes and flats and also cave-type deposits.

5. A common depositional environment for replacement mineralization is the upper surface of volcanic units. These impervious rocks are generally poor hosts, but the existence of narrow fracture fillings and much wider veins where the volcanic rocks are cut by major rakes indicates that mineralizing solutions were capable of passage through them. This has led to fluorine metasomatism of the overlying limestones.

6. Limestone country rock in mineralized areas, particularly in close proximity to major fissure veins or scrin development, has undergone dolomitization and silicification as well as fluoritization. Trace-element studies in wall-rock zones of some mineral veins provide evidence of fluorine, lead, and zinc migration into the wall rocks, whereas a strontium decrease and a zirconium increase have taken place adjacent to the veins.

7. Colour variations and the concentration of fluorite on the eastern side of the orefield reflect a thermal zoning and an easterly derivation for the mineralizing solutions, but the existence of additional fluorite-rich areas away from the eastern margin suggests the presence of more than one source and a more complex mineralization history.

8. Fluid inclusion studies on fluorite indicate filling temperatures of 140°C to 60°C and a salinity of 18 to 30 percent by weight of NaCl. The mineralizing solutions which give rise to them are considered to be a mixture of juvenile fluids carrying Pb, Zn, F, and Ba and connate brines.

CONCLUSIONS

The foregoing summary provides sufficient evidence to support the view that fluorspar deposits in Derbyshire were epigenetic and the product of a telethermal primary mineralization in a structurally controlled environment. There are many areas in Britain where mineralization can be related to events which commenced in early Permian times and a comparison is made with two of these to put the genesis of Derbyshire deposits into perspective.

In southwest England some 250 miles away, metalliferous deposits and associated gangue minerals are clearly related to hydrothermal fluids of juvenile origin that emanated from the cooling Hercynian granites. Fluid inclusion studies by Sawkins (1966b) have shown that the filling temperatures for fluorite from this area were in the 100°C and 200°C range, the salinity was 12.8 to 13.5 percent by weight NaCl, and the Na/K ratio was 6.7 to 9.5.

In the North Pennines, 120 miles away, where fluorspar-rich veins cut similar Lower Carboniferous rocks, but in a different geological setting, Sawkins has indicated that fluorite was deposited between 100°C and 200°C, the salinity of the hydrothermal solutions was approximately 20 percent by weight NaCl, and the Na/K ratio was 6.8 to 12.4. Baryte crystallized at temperatures down to 50°C from solutions with a Na/K ratio of 15.3 to 46.

There is still a lot to learn about the origin of the Derbyshire fluorspar mineralization, and it is hoped that further information from fluid inclusion studies, particularly the Na/K ratio, and other geochemical data will throw more light on the nature of the ore-forming fluids. The writer favours the view that the mineralizing elements Pb, Zn, F, and Ba came from below and were related to a magmatic source. It is possible that connate waters and the rocks through which the mineralizing solutions passed could have contributed to the chemical makeup of these solutions by the time they reached the environments of deposition. An increase in geothermal gradient sufficient to promote movement of hydrothermal solutions is also considered to be related to a deep-seated magmatic source located in areas where previous volcanic activity has indicated crustal instability, particularly on the eastern flank of the orefield.

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GEOLOGY OF MEXICAN FLUORSPAR DEPOSITS

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ABSTRACT

Mexico has been the world leader in production of fluorspar since 1956. The main producing districts are in the states of San Luis Potosi, Guanajuato, Coahuila, Chihuahua, and Durango. The contact between the Lower Cretaceous limestones and the Tertiary intrusive and extrusive rocks of rhyolitic composition has been very favorable for the deposition of large chimneys and cave fillings of high-grade fluorspar. Important production comes from narrow high-grade mantos and veins in the upper section of the Georgetown limestone. Flotation mills in the Parral district produce acid-grade concentrates from lead-zinc tailings which average from 15 to 20 percent fluorspar.

INTRODUCTION

Mexico began shipping fluorspar to the United States in 1938, and by 1956 had become the world leader in production and exportation of metallurgical and acid-grade fluorspar, with a total of almost 1,300,000 meric tons during 1970 and 1971, or 23 percent of the world production. Because of lessening demand in 1972, the production dropped about 18 percent, to a little over one million tons.

The United States now consumes roughly 36 percent of the fluorspar produced in the world, while accounting for only about 5 percent of the world fluorspar production. Because of its proximity to the U.S., and the moderate import duty on fluorspar, Mexico continues to ship over 90 percent of its production to the United States.

The steady rise in demand and price of fluorspar since 1940 stimulated widespread exploration in Mexico. Many large deposits, averaging over 65 percent fluorspar, and innumerable small, high-grade orebodies were discovered. The main producing districts are in the states of San Luis Potosí, Guanajuato, Coahuila, Chihuahua, and Durango (Fig. 1).

In San Luis Potosí and Guanajuato, the contact between the Lower Cretaceous Cuesta del Cura limestone and Tertiary intrusive and extrusive rocks of rhyolitic composition has been very favorable for the deposition of large chimneys and cave fillings, averaging 65 to 85 percent fluorspar.

In Coahuila, the bulk of the production comes from narrow, high-grade mantos and wide veins of lower grade. The Lower Cretaceous Georgetown (Aurora) limestone is by far the most favorable host rock. Some high-grade chimneys have been found at the contacts between acid intrusive rocks and dikes and the Georgetown limestone.

In Chihuahua and Durango, narrow, high-grade veins are found in the middle to late Tertiary volcanic series. Fluorspar is a major gangue material in the lead-zinc veins of the Parral district. The tailings being processed by two acid-grade flotation plants average 15 to 20 percent fluorspar.

Mexico's reserves are conservatively estimated at 32,000,000 short tons, averaging well over 35 percent fluorspar. Improvements in mining methods, mechanization, milling procedures and transportation facilities in the last two decades have enabled Mexico to greatly increase its productivity.

Governmental policy in the last few years has favored the construction of flotation mills and hydrofluoric acid plants, which has led to a corresponding drop in the exportation of metallurgical spar.

DESCRIPTION OF PRINCIPAL DISTRICTS

State of Coahuila

The state of Coahuila now produces approximately 30 percent of the total fluorspar produced
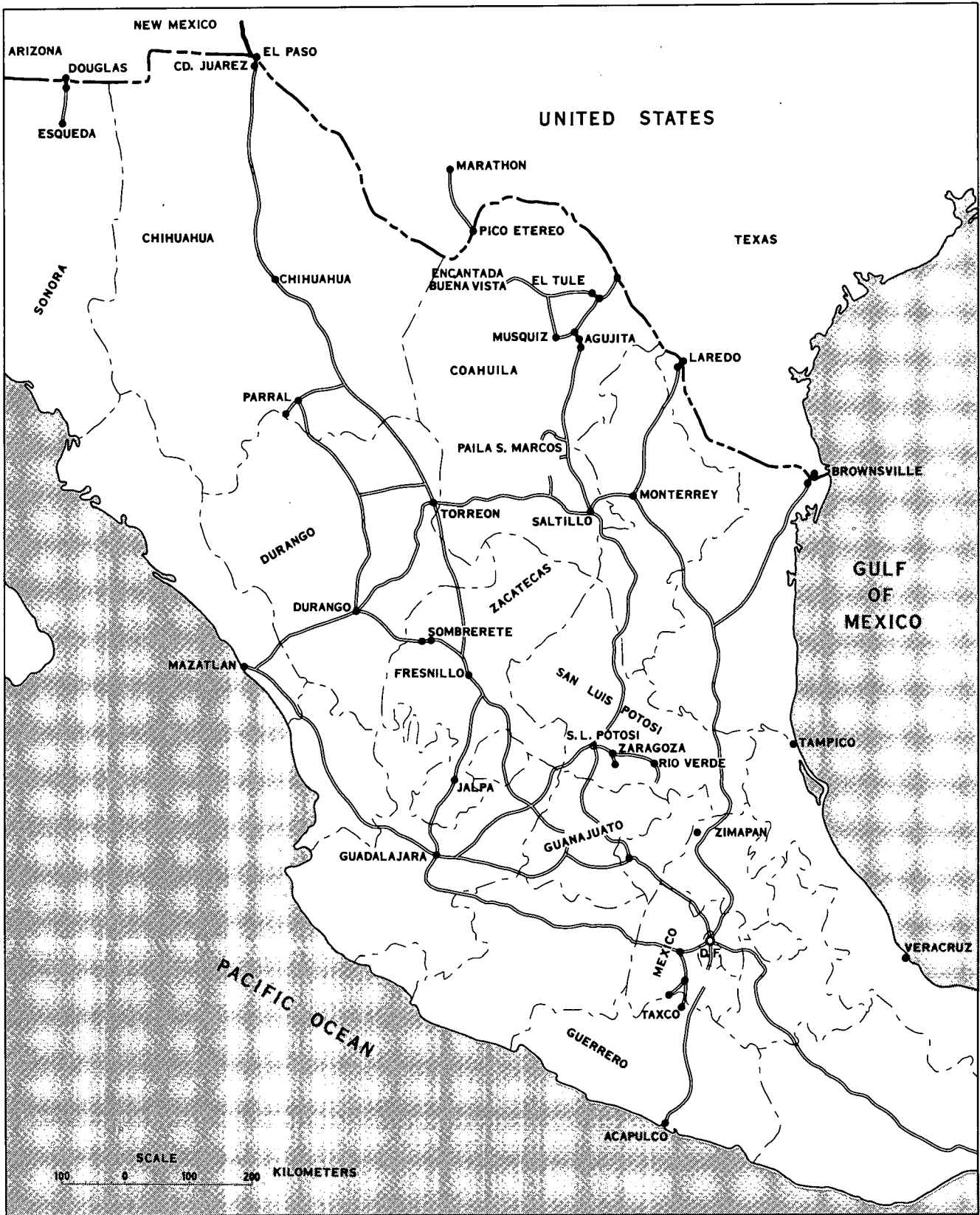
Figure 1.   Index map of Mexico.

in Mexico. Commonly associated minerals are calcite, quartz, barite, hematite, limonite, celestite, and bertrandite.

STRATIGRAPHIC COLUMN

Series and Group	Formation	Approximate Thickness (Meters)
Gulf Series, Eagle Ford Group	Boquillas limestone	150-200
	Buda limestone	25
Comanche Series (Upper Albian), Washita Group	Del Río Shale	3
	Georgetown (Aurora) limestone	350
	Kiamichi limestone	70?
Comanche Series (Middle Albian)	Fredericksburg-Edwards limestone	80?
	Comanche and Walnut Park formations	80?

Pico Etereo District

The Aguachile deposit is located in northwestern Coahuila near the Big Bend National Park in Texas. From 1953 to 1960, this area shipped over 250,000 tons of metallurgical spar by rail to Marathon, Texas.

This deposit has been described as an example of intrusive doming, followed by cauldron subsidence and the development of ring and arcuate dikes of rhyolitic composition. A plug of quartz microsyenite subsequently intruded the south-central portion of the sunken block.

The largest fluorspar deposits occur in limestone along the contact with dikes of rhyolite porphyry. These deposits occupy fault zones in local, intensely brecciated areas in contact zones along the downthrown side. The Edwards, Georgetown, Buda, and Boquillas limestones served as host rocks in one part or another, but the most important orebodies were formed by a combination of replacement and void filling in the Georgetown limestone. The Buda limestone was the second best host. Some orebodies are chimney shaped; others are elongated parallel to the contact, extending irregularly out into the contact zone.

Three stages of mineralization have been determined. The rhyolite and fluorspar probably came from the same source at different stages of the magmatic cycle; the quartz microsyenite may be a differentiate of the same parent magma. The average composition is as follows: CaF_2, 60 to 80 percent; $CaCO_3$, 12 percent; SiO_2, 5 percent; and bertrandite ($Be_4(OH)_2SiO_7$), 0.3 percent. Outside of Aguachile, other known deposits contain less than 50 parts per million of beryllium. The Mexican government declared beryllium a national reserve in 1952, and special permission must be obtained to work these deposits.

Production since 1966 has exceeded 100,000 tpy (tons per year) of combined acid and metallurgical spar. A 400-ton-per-day mill processes fluorspar from the Aguachile and Cuatro Palmas mines.

The Cuatro Palmas and La Facil orebodies are located several kilometers northwest of Aguachile, and have produced a substantial tonnage from open-pit operation, averaging over 70 percent fluorspar. Both deposits are localized along the faulted contact of a 1.8-kilometer rhyolite dike and strongly brecciated Georgetown limestone.

The Cuatro Palmas deposit is in the form of an inverted cone, with a 90-meter diameter on the outcrop. Mineralization occurred in several stages, with a rhythmic replacement of the limestone and by direct precipitation in voids.

La Facil deposit is a relatively small and shallow, tabular orebody, measuring about 60 by 15 meters, with a fluorspar content of 85 percent.

The Mal Abrigo deposit is located northeast of Aguachile along the faulted contact between an intrusive rhyolite porphyry and the Georgetown limestone. The vein has been worked along strike for over 300 meters, with oreshoots up to 10 meters in width. Total production has exceeded 50,000 tons of highly sorted metallurgical spar.

El Tule District

Located in north-central Coahuila, the El Tule district covers an area of 80 square kilometers. Total production of highly sorted fluorspar from narrow mantos has exceeded 50,000 tons.

The ore zone is in the top few meters of the Georgetown limestone, and in places the fluorspar partially or completely replaces the thin Del Río shale. The beds are almost flat, and the fluorspar occurs as discontinuous mantos averaging about 0.6 meter in width and from 50 to 80 percent fluorspar. Celestite ($SrSO_4$) is a very common gangue material with minor calcite and barite. Certain deposits contain a high percentage of silica. As water is very scarce in the region, dry

classification using compressed air has been attempted in a pilot plant at the San Miguel mine to separate the fluorspar from the celestite.

The orebodies are small and not adaptable to large-scale operation. Extraction of the ore is by means of short crosscuts and shallow winzes. Careful hand sorting of the ore yields a high-grade product.

All of the deposits in the district have been found by mapping of the Del Río shale and the Georgetown limestone, and the sinking of numerous shallow prospect pits. Areas where the Del Río shale is thickest have proven most favorable for the deposition of the widest and better grade mantos.

Encantada-Buenavista District

This district, which comprises about 500 square kilometers, continues to be the most important producer of fluorspar in Coahuila. The Muzquiz plant has a capacity of 600 tpd (tons per day) and produces 150,000 metric tons of fluorspar per year.

The fluorspar occurs as discontinuous mantos averaging about 1.5 meters in width, and in places attaining 6 meters in width. The ore zone is near the top of the Georgetown limestone and in a few places extends into the Del Río shale.

As in the Tule area, there is no apparent relation of ore to intrusive rocks. Some geologists believe the fluorspar to be of possible sedimentary origin, although all the other fluorspar deposits throughout Mexico are clearly of hydrothemral origin.

Mining operations are similar to those in the Tule district. Prospecting in the Del Río shale and the Georgetown limestone is often complicated by an extensive capping of caliche which masks signs of fluorspar mineralization.

Paila-San Marcos District

Located in southeastern Coahuila and covering an area of some 1,300 square kilometers, this district produced an important amount of fluorspar from 1953 to 1965. The ore was obtained from narrow, high-grade mantos and wide fluorspar veins with a high content of calcite gangue. The mantos are confined to the upper section of the Georgetown limestone, average about 0.5 meter in width, and contain over 85 percent fluorspar.

The veins are wide and continuous, averaging several meters in width; some oreshoots are up to 12 meters wide. A number of veins have been mined through a vertical distance of 100 meters. The veins average 50 to 60 percent fluorspar and are usually associated with high calcite gangue, requiring separation by flotation.

The principal deposits all have been worked out, and the area at present has very limited production.

State of Sonora

Esqueda District

The Esqueda district is located in the northwestern part of Sonora and is the only major producer in this state. Prior to 1960, a limited amount of metallurgical spar was produced from selective mining of a wide vein in the Tertiary volcanic series. A 125-ton-per-day flotation mill, installed in 1960, produces acid-grade concentrates.

The oreshoots on veins have been mined for over 200 meters along strike; they average several meters in width and in places open out to a 20-meter width. Narrow sections of the veins are mined by open stoping and wider sections by cut and fill. Extraction of the ore is by means of a 100-meter shaft and by adit.

States of Chihuahua and Durango

Of major importance in Chihuahua are some 40,000,000 metric tons of tailings, averaging from 15 to 20 percent fluorspar. The three principal mines in the Parral district, Santa Barbara, San Francisco del Oro, and La Prieta, have quartz and fluorspar gangue in the lead-zinc veins which occur in shale and andesite. The fluorspar is present through a vertical range of more than 700 meters. A second stage of mineralization formed narrow veins of quartz, fluorspar, and calcite which cut the sulfide veins, filling open fractures in and along the vein and extending for short intervals into the vein walls.

Asarco Mexicana's plant in Parral produces approximately 50,000 metric tons of acid-grade concentrates yearly from the old tailings and will complete a 50-percent expansion in 1974.

The Compañía Minera Frisco mills 2,000 tpd of current tailings, combined with 200 tpd of high-

grade custom ore to produce some 100,000 tpy of acid-grade concentrates. A new plant is under construction to process the old tailings.

Frisco is in partnership with E. I. DuPont de Nemours & Company and the Mexican government in the construction of Mexico's first hydrofluoric acid plant at Matamoros, Tamaulipas, at a cost of 37.5 million dollars. The plant is scheduled to be in production by January 1975. At its capacity of 75,000 tpy of hydrofluoric acid, it will need approximately 160,000 tpy of acid-grade concentrates. Most of this concentrate will be supplied by Frisco. Under government regulations, this plant and others now in the planning stages will have priority on any of the acid-grade concentrates needed to keep the plants running at capacity.

In the Parral area, stripping operations close to the Esmeralda mine produce about 100 tpd for Frisco. Vein-like concentrations of over 65 percent fluorspar are localized along a wide dike of rhyolitic composition. The country rock is shale and monzonite and the vein outcrops range from 3 to 8 meters in width. Diamond drilling results showed a marked weakening of vein structure and increase in silica content at less than 50 meters below the outcrop.

A number of small mines produce high-grade metallurgical spar from narrow veins in the Tertiary volcanic rocks in the transition zone between the Central Plateau and the Western Sierra Madre in south-central Chihuahua.

In the Bermejillo, Durango, area a small production of high-grade fluorspar is obtained from narrow mantos in the Lower Cretaceous limestone.

The Rodeo-Indé area in western Durango produces a regular tonnage of fluorspar from veins 0.5 to 3.0 meters in width in the Tertiary volcanic rocks, often associated with wide rhyolitic dikes. Upgrading of these ores is by mechanical concentration, jigs, washing plants, and by hand sorting to yield over 80 percent fluorspar.

La Colorada property is located in west-central Durango and has a production in excess of 40,000 tpy of over 80 percent fluorspar with about 13 percent silica. The veins are persistent for more than a kilometer in length and vary from 1.0 to 10 meters in width. The country rock is a well-

consolidated conglomerate. Water problems have hampered the development of these deposits below the 40-meter horizon.

States of Zacatecas, Aguascalientes, and Jalisco

Frio District, Zacatecas

The Josefina mine, located 10 kilometers east of Sombrerete, produced over 60,000 tons of 60-percent fluorspar from 1944 to 1953; the mine has been inactive for many years. The fluorspar was deposited along a series of persistent faults in Lower Cretaceous limestone. The main oreshoots are 2 to 4 meters in width and reach a depth of 90 meters.

Jalpa District

In recent years a number of small mines have been producing metallurgical spar in an extensive area covering southern Zacatecas and Aguascalientes. The veins are in tuffs and flows of rhyolitic composition of Tertiary age. They average less than 2 meters in width, but are persistent along strike and contain approximately 60 percent fluorspar. One of the mines produces from a depth of 90 meters. A plant for the production of acid-grade fluorspar, with a 100-ton-per-day capacity, is being constructed in Jalpa.

Bolanos Mine, Jalisco

Located in northern Jalisco, this old silver camp was recently reactivated, and a 400-ton-per-day mill produces concentrates of lead, zinc, and fluorspar. The sulfide veins average over 20 percent fluorspar, and high-grade fluorspar, mined from narrow veins in the north end of the district, is added to the mill feed.

States of San Luis Potosi and Guanajuato

Extensive, high-grade fluorspar deposits were discovered in the Zaragoza and Río Verde districts in the early 1950's. Since that time, constant exploration and development work has promoted a steady increase in the production, which now exceeds 55 percent of the total fluorspar produced in Mexico, principally of metallurgical grade. The faulted and brecciated contact between the Lower Cretaceous limestone and Tertiary volcanic rocks is considered to be the major control of the mineralization.

Zaragoza District

La Consentida and Esperanza deposits are located 40 kilometers southeast of the city of San Luis Potosí and have been worked by Pennwalt since 1955. Both orebodies are located along a persistent, northwestward-trending fault which has dropped the rhyolitic extrusive rocks relative to the nearly horizontal Cuesta del Cura limestone. La Consentida deposit was formed by replacement of the intensely brecciated limestone and rhyolite, as well as by open-space deposition in large solution caves. The orebody strikes northwestward, plunges steeply to the southwest, and measures approximately 110 by 80 meters. It has been mined by open-pit operation to a depth of 100 meters. Diamond drilling below the bottom of the pit showed tapering roots which terminate about 60 meters below the floor of the pit. This remaining ore will be mined by means of a ramp and truck haulage. The estimated grade is about 70 percent fluorspar with 16 percent silica.

The Esperanza orebody is located 300 meters to the northwest along the strike of the contact of La Consentida deposit. It is much smaller than La Consentida, with a length of about 50 meters and a width of about 20 meters. A tunnel driven at 60 meters below the operating pit floor shows a considerable increase in size. The estimated grade is about 75 percent fluorspar with 20 percent silica. Diamond drilling of the contact between the two orebodies failed to find any ore.

The fluorspar is crushed to 2 or 3 inches, hand sorted on picking belts, and screened to remove the fines. Hand sorting removes about 5 percent of the waste rhyolite and limestone fragments. This product is trucked to a storage yard in San Luis Potosí where the fluorspar is further crushed, screened, jigged, and washed to remove the fines. The ore is assayed and blended in the yard to meet market specifications. Unmarketable fines are sold to flotation mills.

The Cuevas mine is affiliated with the Noranda Mines of Canada, and is located about 1.5 kilometers south of La Consentida. This deposit also occurs on the faulted rhyolite-limestone contact, but the bulk of the mineralization is in the highly altered and fractured rhyolite. A series of oreshoots have been developed on the 70- and 120-meter levels, driven from a vertical shaft. These orebodies have horizontal dimensions of 50 by 40 meters and are separated by 30 to 40 meters of barren ground. A major new orebody to the south is said to have been discovered by gravimetric studies, followed by diamond drilling. Mining is by a rill-type, cut-and-fill method, and by shrinkage stoping.

A recently completed mill produces some 30,000 tpy of acid-grade fluorspar from fines and low-grade ore. In 1971 Las Cuevas produced 202,000 tons of metallurgical spar. The reserves are said to exceed 3,000,000 tons of ore that is over 65 percent fluorspar.

Rio Verde District

El Refugio mine, the principal producer in the state of Guanajuato, is located 45 kilometers southwest of the town of Río Verde, on the south bank of Río Santa Maria, the main river in the area. Transportation of the ore from the mine to the mill over 62 kilometers of winding, narrow road is difficult and expensive.

El Refugio orebody is believed to be a breccia pipe almost completely replaced by fluorspar. It occurs at the contact between limestone and a small intrusive body of rhyolite. Rhyolite flows cap the limestone in the immediate vicinity of the mine. The orebody measures 70 by 40 meters and has an easterly plunge ranging from 45 to 90 degrees. Diamond drilling shows a vertical extension of about 300 meters. The ore grade is approximately 85 percent fluorspar with 4 percent silica.

The upper section of the orebody was mined by open-pit methods; the present production is from underground mining and exceeds 100,000 tpy, of which 60,000 tons are acid-grade concentrates. Industrias Peñoles and Allied Chemical, the owners of the mine, plan to double the mill capacity as well as the production of metallurgical spar. No serious water problems have been encountered in mining operations at considerable depth below the river level.

El Zapote mine is the property of the Compañia Minera La Valenciana and is located about 25 kilometers south of Río Verde. The orebody is a nearly vertical chimney, approximately 60 meters in diameter, in the Lower Cretaceous limestone close to the contact with Tertiary volcanic rocks. Underground mining has reached the

107-meter level. The ore is hand sorted at the mine and trucked to a washing plant in Río Verde. The production is about 60,000 tpy of 60 to 80 percent fluorspar.

La Ilusion mine is located near the Zapote mine and has very similar characteristics. The orebody is over 10 meters in width and is worked by open-pit methods. The owners are Industrias Peñoles and Fluorita de Mexico (Continental Ore Co.).

La Rosita mine is located 38 kilometers southwest of Río Verde and is under the same ownership as La Ilusion mine. Industrias Peñoles plans to double the production from both of these mines.

The orebody is an elliptical chimney over 15 meters in width in a highly folded Lower Cretaceous limestone. Rhyolite flows are present about 300 meters to the south of the mine. The production is about 150,000 tpy of metallurgical spar, processed by mechanical concentration. A part of this production will be converted to acid-grade concentrate at a new plant under construction.

State of Mexico

Zacualpan District

The first flotation mill in Mexico for acid-grade fluorspar was a 70-ton-per-day plant at Zacualpan; it started production in 1951. A number of wide, persistent veins have been worked in the region to a depth of 200 meters. More than 100,000 metric tons were produced from 1938 to 1962.

The orebodies contain 60 to 70 percent fluorspar, and are localized within fault zones in Mesozoic sericite schists, quartzites, and shales. A variety of Cenozoic intrusive bodies occur in the area.

Although large reserves remain in the various veins, the district has been inactive for a number of years due to legal problems in the claim ownership. The abundant barite gangue is said to cause serious difficulties in the flotation process.

State of Guerrero

Taxco District

La Azul and El Gavilán deposits are located about 10 kilometers northeast of Taxco. They produced over 100,000 tons of fluorspar during the period 1939 to 1948. Both deposits have been inactive since 1948.

La Azul orebody occurs close to the contact of the Morelos limestone and dolomite of Early Cretaceous age with the overlying Balsas conglomerate and the Tilzapota rhyolite series of Eocene-Oligocene age. Major northeastward-trending faults traverse the area.

A small, irregular body of rhyolite intruded the limestone; subsequent brecciation and shattering of the margin of the intrusive rock and the limestone provided a favorable locus for the fluorspar mineralization. The main chimney has a diameter of 12 to 20 meters and plunges 70 to 80 degrees to the northeast. The average grade is 63 percent fluorspar, 27 percent SiO_2, and 2.5 percent $CaCO_3$. The orebody was worked by open-pit mining and partially explored by short levels from a 55-meter shaft. Some diamond drilling was done from the surface. Estimates of reserves range from 200,000 to 500,000 metric tons.

EXPLORATION FOR FLUORSPAR

Although some major ore deposits have been discovered in Mexico by untrained prospectors, most of the large, successful fluorspar operations have been the result of diligent geological exploration. This includes regional and areal reconnaissance and mapping and utilization of aerial photos to delimit areas for more detailed studies. These may consist of geological mapping with topographic controls, trenching, sampling, diamond drilling, and development work by prospect pits, shafts, adits, etc.

Obviously, the most successful exploration has been in determining the extensions of known mineral trends, intersections of major structural features, and along the contact between acid igneous rocks and favorable limestone units. Mapping of the Del Río shale and the Georgetown limestone in northern Coahuila and the studies of structural features and alteration along the extensive contact between Tertiary volcanic rocks and the Lower Cretaceous limestones throughout the Central Plateau, followed by diamond-drilling programs or development work in the more promising areas, have led to the discovery of many commercial fluorspar deposits.

Gravimetric studies have had some limited success in determining local extensions of large, massive fluorspar deposits in the Cuevas mine.

Geochemical sampling and analysis of soil, rock, and stream sediments have proven useful in the search for new fluorspar deposits or to locate possible extensions of known ore zones, using the most commonly associated elements such as Hg, Ag, Pb, Cu, Zn, Be, and Sr.

U.S. TARIFF ON FLUORSPAR

Since June 1951 the following U.S. tariff has been in effect:

	Long Ton	Short Ton
Over 97 percent CaF_2	$2.10	$1.88
97 percent, or less, CaF_2	$8.40	$7.50

MEXICAN TAXES ON FLUORSPAR

There is a 3-percent production tax levied on the value per ton of fluorspar, according to the official price set by the Mexican government.

There is a 15-percent export tax, plus a 2-percent surcharge, which is levied on the value per ton of metallurgical or acid-grade spar, according to the official price set by the Mexican government.

One-half of the government portion of these taxes, which amounts to about 85 percent of the total, is refunded to the Mexican-owned companies (about 51 percent). Special subsidies are granted to small mines and to newly formed companies.

PRICES

Mexican fluorspar, short ton f.o.b.

	Jan. 1973	Jan. 1971
Metallurgical (effective CaF_2, 70 percent)		
Tampico, vessel	$50.00	$31.15
Mexican border, cars	$48.50	$30.15
Acid grade (97 percent) Eagle Pass, bulk	$64.50	$52.00

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GEOLOGY OF FLUORSPAR DEPOSITS OF THE WESTERN UNITED STATES[1]

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ABSTRACT

The Western United States is one of the fluorine-rich provinces of the world, and it contains numerous districts and mines that have produced some fluorspar. However, few have had major or sustained fluorspar production. The Western States have accounted for approximately 20 percent of the total U.S. production of CaF_2 to date.

Fluorine in nature is dominantly in the combined form and tends to concentrate in specific geologic environments in the crustal rocks of the Western United States. Preferred igneous associations are silicic and alkalic extrusives and intrusives, complex pegmatites, carbonatites, and contact aureoles of these. Sedimentary rocks containing concentrations of fluorine are volcaniclastic, lacustrine, evaporite, marine carbonate, and marine phosphorite beds. Major concentrations of fluorine in the West occur in hydrothermal deposits distributed among a wide variety of geologic environments in the form of veins, mantos, pipelike bodies, stockworks, and disseminations.

Two general groups of Tertiary late-magmatic and hydrothermal fluorite-bearing deposits are recognized in the Western United States: (1) those associated with intrusive igneous rocks and (2) those not associated with intrusive igneous rocks. Each group contains a wide variety of types of deposits ranging from metal deposits with minor fluorite gangue to fluorspar deposits with trace amounts of metals. Similarities in geology and geochemistry suggest that the two groups formed from the same kind of magmatic-hydrothermal system; the first group represents deposition at depth and the second group represents deposition at or near the surface. The first group includes fluorite within or directly associated with alkalic or silicic-alkalic intrusives. Fluorite in these deposits formed at temperatures ranging from 150°C to 500°C, and from solutions that were relatively saline ($\geq$ 20 weight percent) and in part magmatic, in part pneumatolytic, and in part hydrothermal. Economically important fluorspar deposits of this type are pipelike bodies in large breccia zones and massive fine-grained bodies in tactites. The second group includes fluorite not associated with larger bodies of intrusive igneous rock. Although some of this fluorite is within or directly associated with minor hypabyssal bodies or with extrusive bodies of basalt or rhyolite, much has no apparent igneous connection. Fluorite in these deposits formed at temperatures under 200°C and from very dilute fluids. Economically important fluorspar deposits of this type include large veins and mantos in silicic igneous and metamorphic rocks and calcareous sedimentary rocks, and dispersed fluorite in highly silicified rocks.

Fluorspar deposits with most promise for future exploitation are the Tertiary late-magmatic and hydrothermal deposits. Other types of fluorine concentrations that deserve consideration are complex pegmatites, carbonatite complexes, marine phosphorites, and lacustrine and volcaniclastic sedimentary rocks. The possibilities are excellent in all these for developing large low-grade deposits with possible coproducts or byproducts.

INTRODUCTION

This report is a review and summary of the geology and geochemistry of fluorine in crustal rocks of the Western United States. A comprehensive report on the subject, with emphasis on the mineral fluorite and on resources of fluorspar, is being prepared by the U.S. Geological Survey (D. R. Shawe, editor); descriptions, relative sizes, locations, and references to each individual fluorspar deposit are presented by Worl, Van Alstine, and Heyl (1973). Production information can be obtained from the U.S. Bureau of Mines annual yearbooks; MacMillan (1970) reported a current summary of domestic uses and the political distribution of production and consumption of fluorine. In the present report, fluorspar refers to mineral deposits in which fluorite is a major component whether or not the deposit is now a commercial fluorine source, and fluorite occurrence refers to mineral deposits in which fluorite is a minor or trace component even though it may have possible byproduct potential. The CaF_2 content is the grade of fluorspar ore, and production and consumption figures are given in terms of short tons of CaF_2.

The Western United States is one of the fluorine-rich provinces of the world as indicated by large areas containing an abundance of fluorspar deposits and fluorine occurrences (Figs. 1, 2, and 3) and the fact that these are also areas of fluorine-rich igneous rocks (D. R. Shawe, personal commun., 1973). Many deposits in the West have produced ore or are currently producing fluorspar (Fig. 4). However, very few have produced more than a few hundred tons of CaF_2, and the major producers each have total production figures of only around 750,000 tons CaF_2. Production of fluorspar in the Western United States to 1970 amounted to 2,674,600 tons CaF_2, or about 20 percent of the total U.S. production to that date. The major producing states have been Colorado, Montana, Nevada, New Mexico, and Utah.

Production of fluorspar before 1900 was for local consumption as a flux in smelters. Fluorspar was reportedly taken, for use in local smelters, from the Jamestown and Evergreen districts, Colorado, as early as 1873 (Van Alstine, 1964, p. 163) and from the Gila district, New Mexico, in 1880 (Williams, 1966, p. 3). During the period 1901 to 1914, hand-sorted crystals and pure screenings of fluorite from the Castle Dome lead district, Yuma County, Ariz., were shipped to California to be used as a flux in producing cement clinker (Van Alstine and Moore, 1969, p. 349). Several other districts reported fluorspar production during this period but gave no indication of the destination or use of the ore. The first major fluorspar production came during World War I when 42,000 tons of CaF_2 were shipped in 1918 (Fig. 5), mainly from Colorado with lesser amounts from New Mexico, Utah, Arizona, Nevada, and Washington. From the end of World War I until World War II, fluorspar production in the West was sporadic and minor, generally less than 10,000 tons CaF_2 annually. During World War II many districts in Colorado, New Mexico, Utah, Nevada, Arizona, Idaho, Texas, California, and Wyoming produced fluorspar, and all known deposits were explored and evaluated. Following the end of World War II, fluorspar production in the West remained relatively high during the 1950's and increased to an alltime annual high of 182,000 tons CaF_2 in 1958. This tonnage was about 55 percent of the U.S. total shipments that year (Fig. 5). However, this production dropped sharply the following year because several mines in the West ceased operations. During the 1960's fluorspar shipments from the West remained static at about 50,000 tons CaF_2 annually, mostly from three mines located in Colorado, Montana, and Nevada. With the recent renewed interest in fluorspar as a commodity and a concurrent price rise, shipments from the West have more than doubled in the last few years and currently account for roughly 30 percent of the U.S. total fluorspar production. Still, the shipments from the West account for only 6 percent of the total U.S. consumption.

Although crustal rocks in parts of the Western United States are fluorine rich, there are few large fluorspar districts located here and very few districts with any sustained production. Fluorspar production in the West is affected by price fluctuations, distance to markets, competition (both foreign and domestic), and, most importantly, the very nature of the type of fluorspar deposits exploited to date. Most are hydrothermal deposits that form isolated pods and veins or high-grade
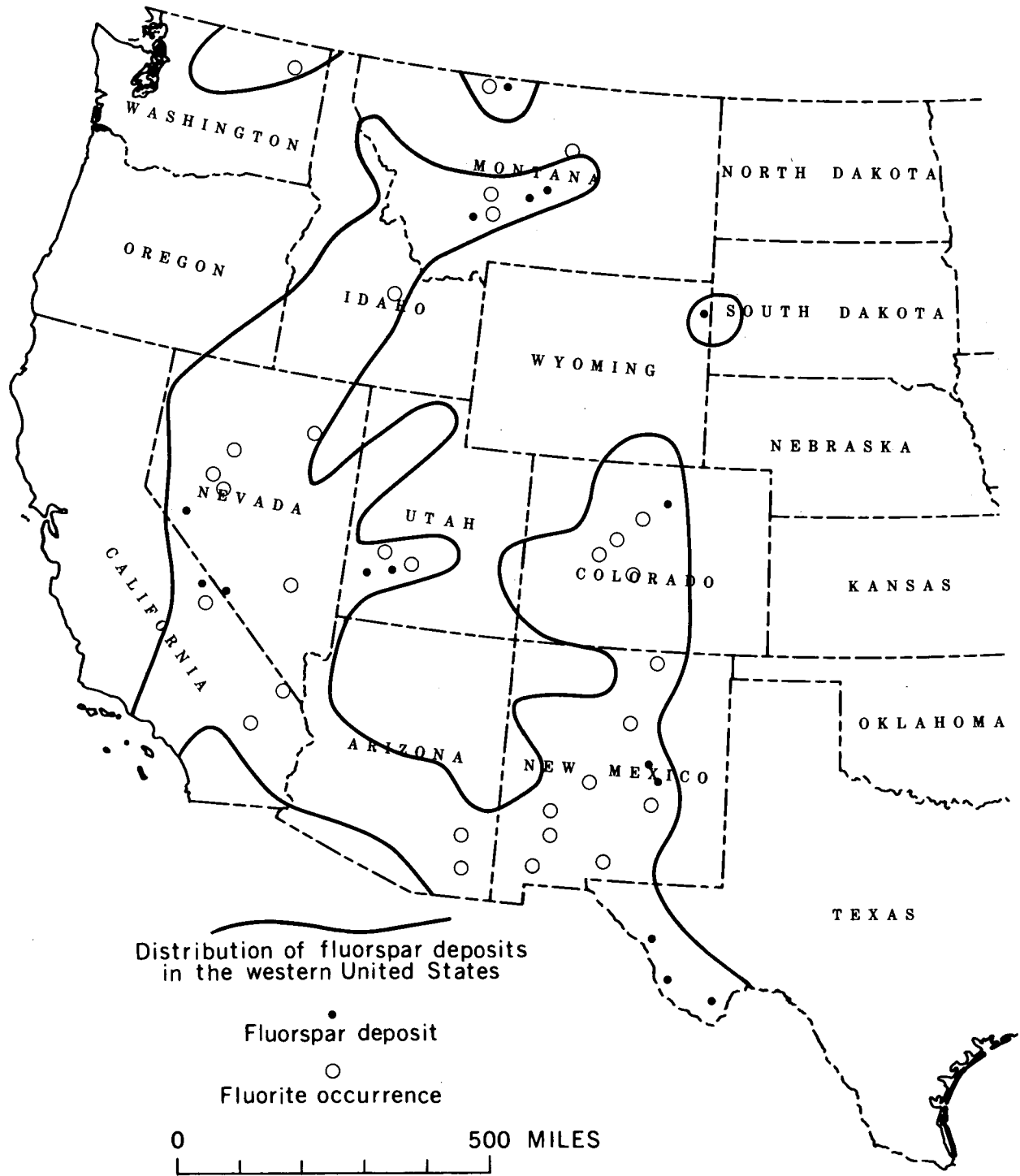
Figure 1. Map showing Tertiary late-magmatic and hydrothermal fluorspar deposits and fluorite occurrences associated with intrusive rocks.

pods and veins within larger but uneconomic fluorspar deposits. Although high in CaF_2, most of these deposits are small (a few thousand tons), discontinuous and isolated, and, not uncommonly, completely mined out within a short time. Other hydrothermal fluorspar present, generally within producing districts, has been unproductive because of low grade, beneficiating problems mainly owing to the intimate intergrowth of fluorite and silica, or the lack of recognition of
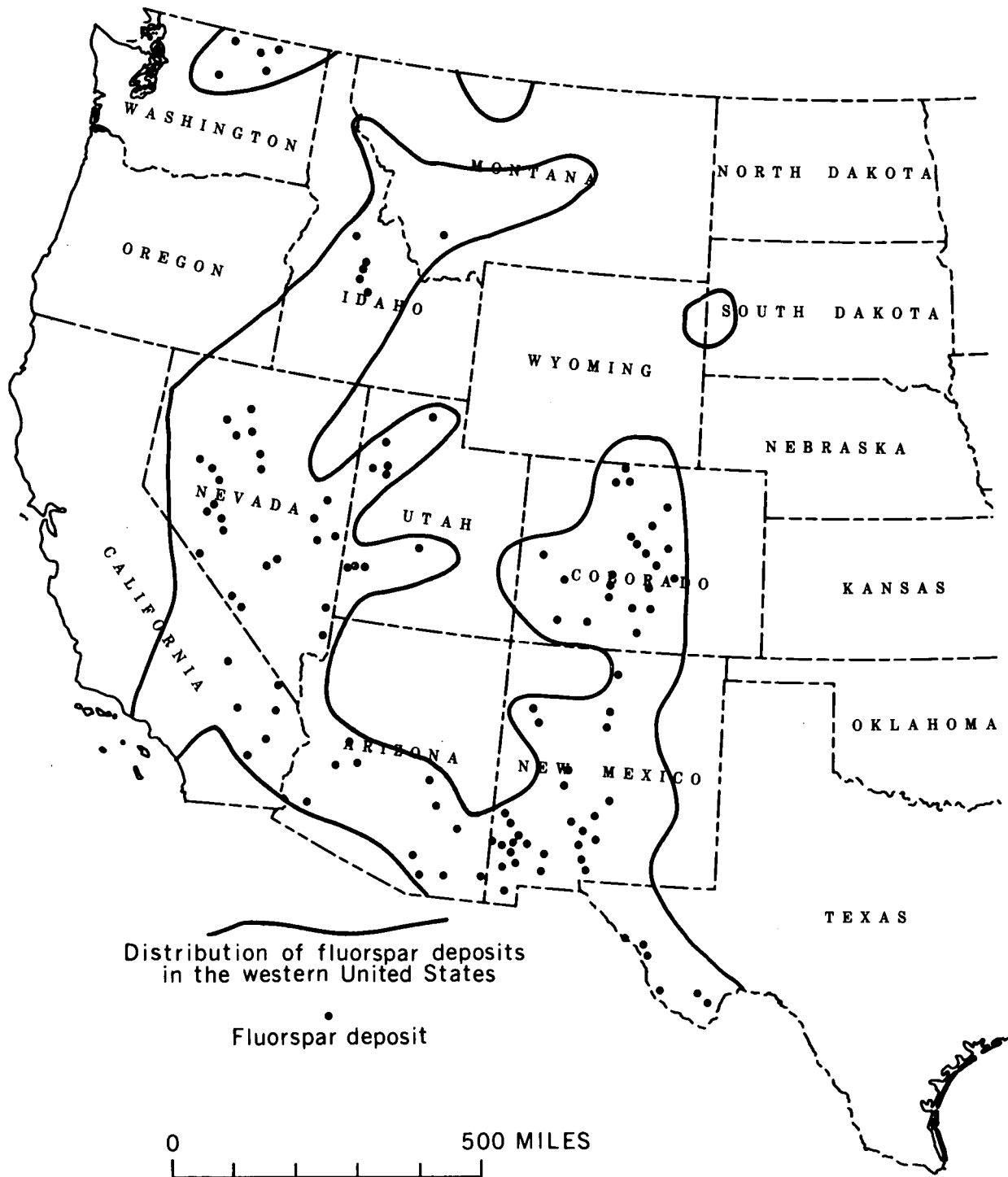
Figure 2. Map showing Tertiary hydrothermal fluorspar deposits not associated with intrusive igneous rocks.

the presence of fluorite. The deposits exploited to date are best suited to relatively minor but steady mining operations such as the present operations at the Crowell mine, Fluorine district, Nevada, and the Burlington mine, Jamestown district, Colorado, both longtime and continuous producers. Some of the recent exploration activity in the West has been directed toward finding or outlining large-tonnage, low-grade deposits with possible coproducts or byproducts.

In any discussion of fluorine in the Western United States, consideration must be given to

Distribution of fluorspar deposits in the western United States

O
Fluorite occurrence

0   500 MILES
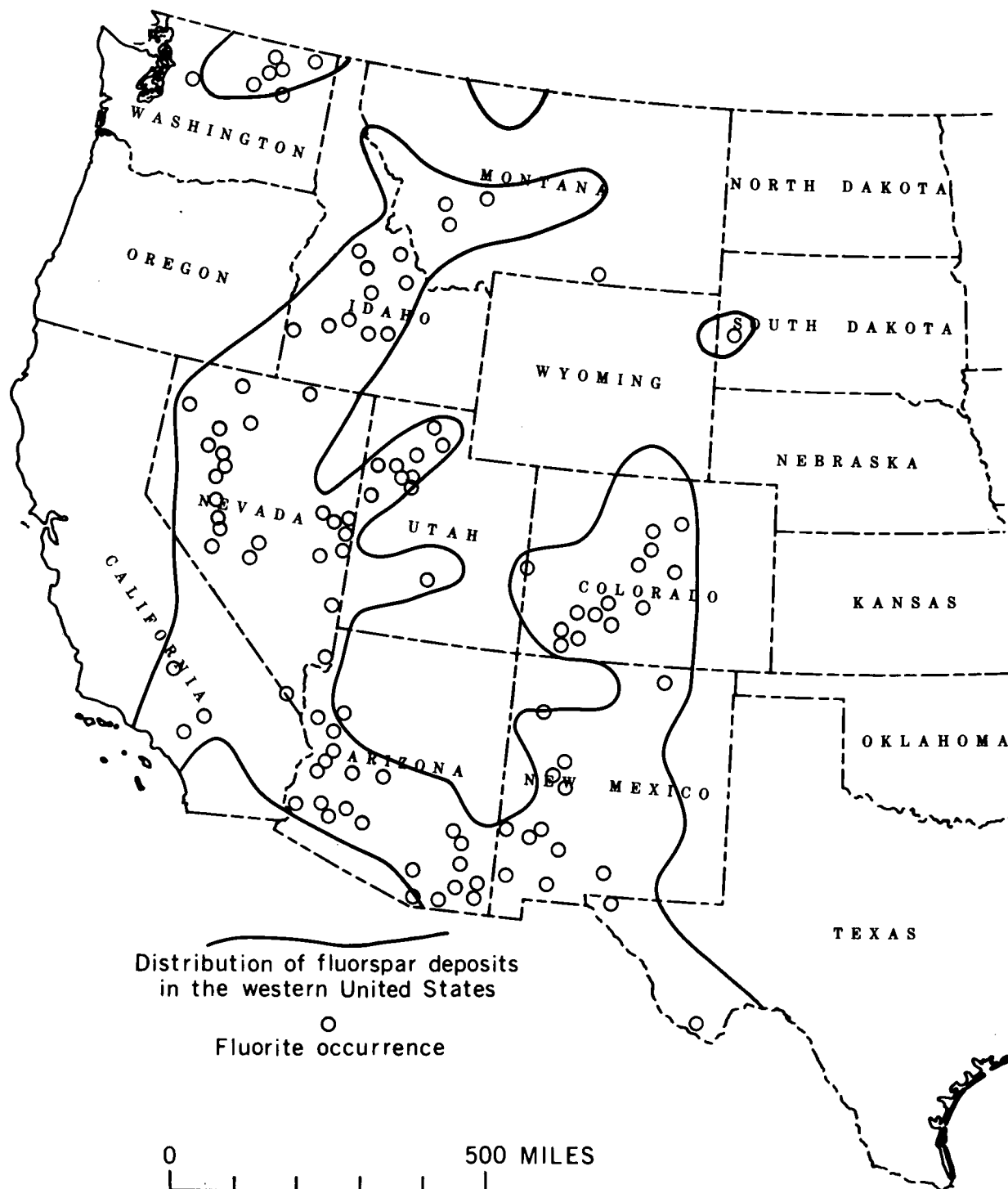
Figure 3. Map showing Tertiary hydrothermal fluorite occurrences not associated with intrusive igneous rocks.

the total distribution of fluorine, not just to the commercially important late-magmatic and hydrothermal deposits. Although poorly documented and generally unexplored in the West, other types of fluorine occurrences constitute commercial deposits elsewhere in the world and deserve consideration here.

GEOLOGIC ENVIRONMENT OF FLUORINE

Geochemistry and Mineralogy

Fluorine is a volatile element, and large amounts of gaseous fluorine are given off in some active volcanic areas. Most fluorine in nature, however, is found combined in solid form, either in fluoride
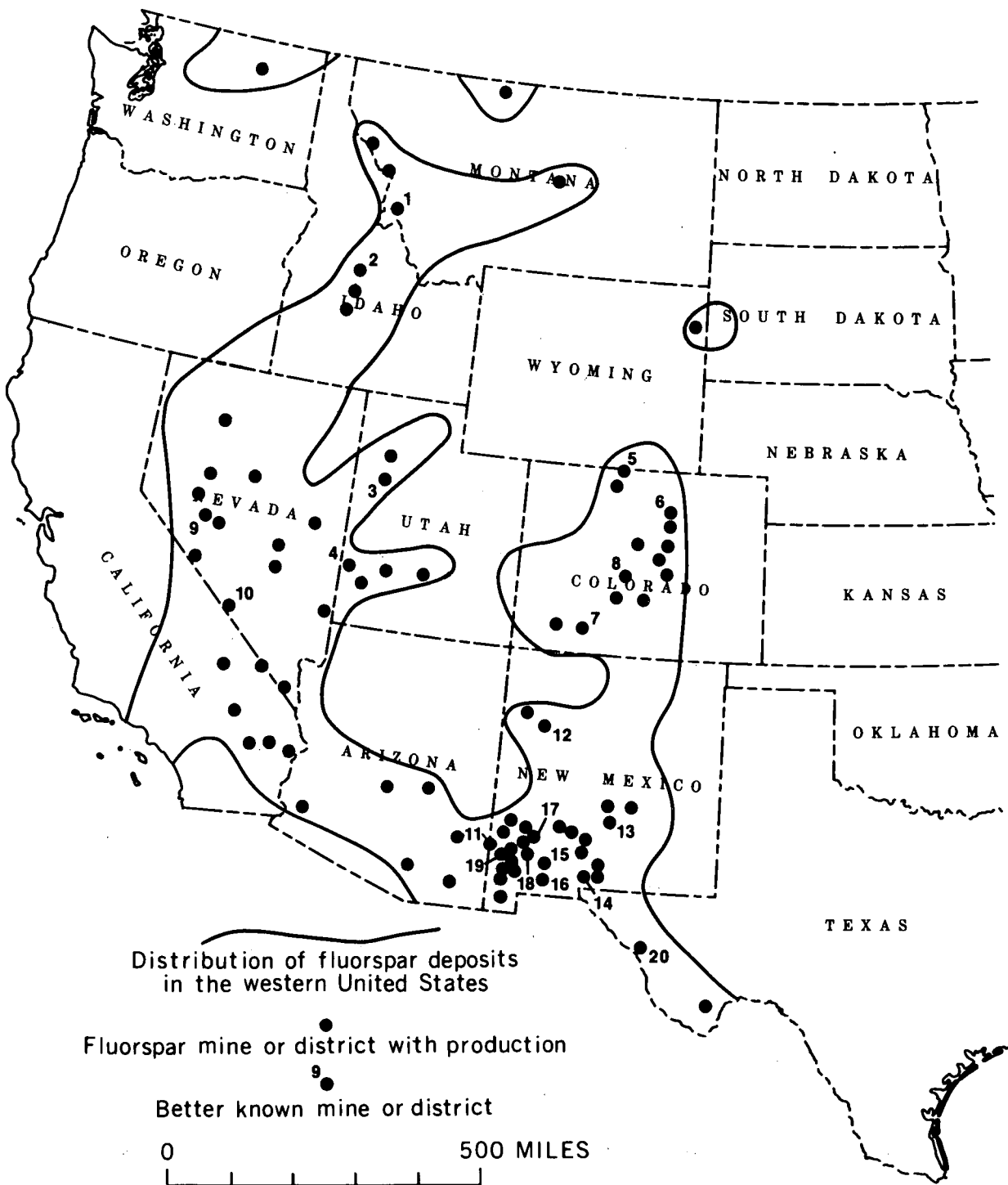
Figure 4. Fluorspar mines or districts with past or present production. 1, Crystal; 2, Meyers Cove; 3, Thomas Range; 4, Indian Peaks; 5, Northgate; 6, Jamestown; 7, Wagon Wheel Gap; 8, Browns Canyon; 9, Baxter mine; 10, Crowell mine; 11, Duncan area; 12, Zuni Mountains; 13, Sierra Caballo; 14, Tortugas; 15, Cooks Peak; 16, Fluorite Ridge; 17, Gila; 18, Burro Mountains; 19, Redrock area; 20, Eagle Mountains.
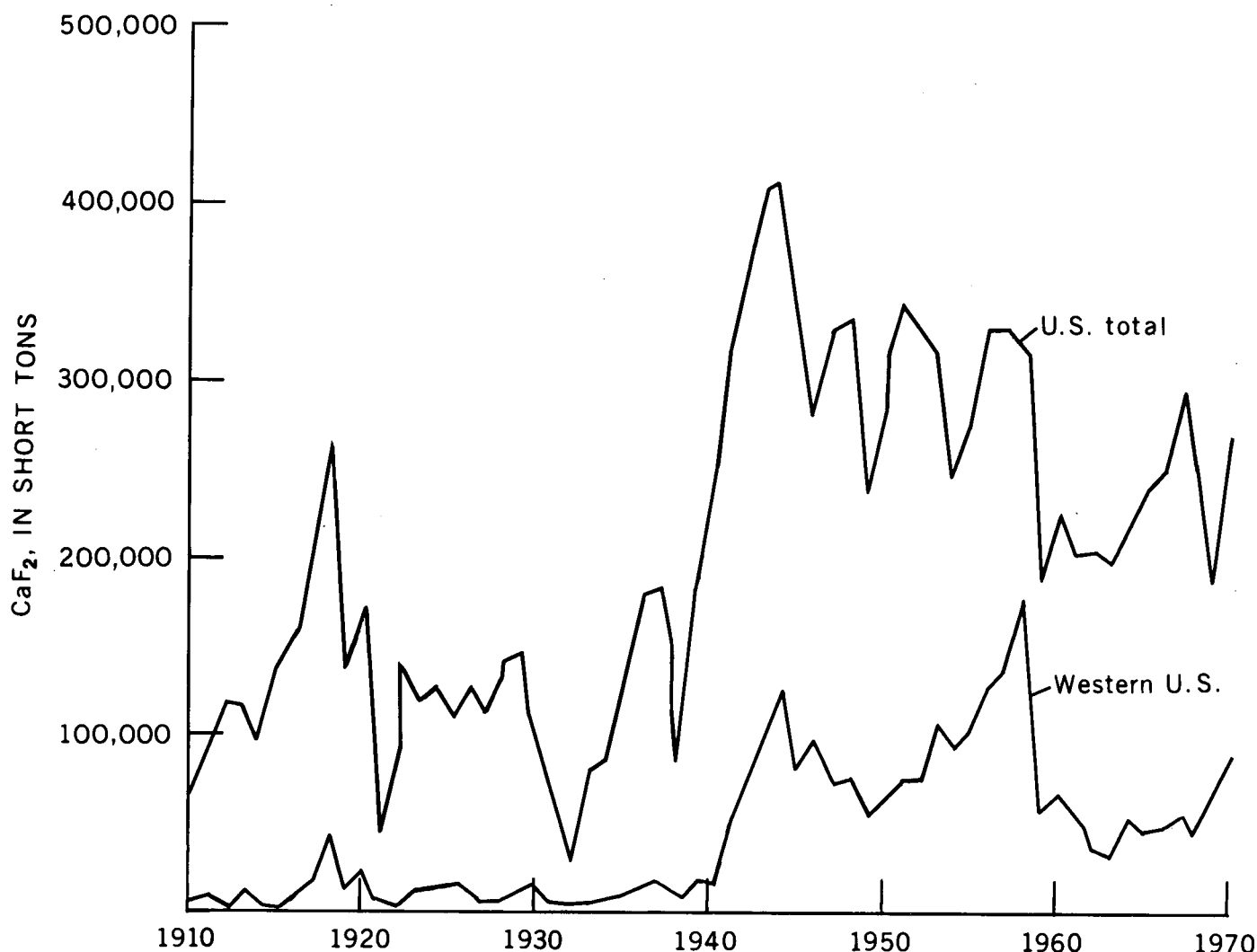
Figure 5. Graph showing fluorspar (CaF$_2$) production in Western United States and total U. S. production: 1910-1970.

minerals or as a substitute in silicate or phosphate minerals. The radius of the fluoride ion is very close to that of the hydroxyl and oxygen ions, allowing easy substitution of one for the other in the silicate and phosphate minerals. Fluorite (CaF$_2$) is geologically the most abundant and economically the most important fluorine mineral in the Western United States; the other fluoride minerals are very rare. Topaz (Al$_2$SiO$_4$(F,OH)$_2$) is common, but not yet a commercial source of fluorine. Carbonate fluorapatite (Ca$_5$(PO$_4$,CO$_3$)$_3$F), the ore mineral of phosphate rock, is widespread in the Western United States, and is a potential source of fluorine as a byproduct of the processing of phosphate rock.

Distribution of Fluorine in Crustal Rocks

Although fluorine is widespread throughout the lithosphere, it tends to be concentrated in fairly specific igneous, sedimentary, metamorphic, and hydrothermal environments (Worl, Van Alstine, and Shawe, 1973). For purposes of discussion, the distribution of fluorine has been classed into fluorine associated with igneous rocks, sedimentary rocks, metamorphic rocks, and fluorine in hydrothermal (hot water) deposits. The classes overlap and intergrade somewhat but still provide a convenient basis for further discussions.

In igneous activity fluorine is considered as a characteristic component of the volatile phase of

magmatic differentiation. More specifically, fluorine is concentrated in alkalic and silicic plutonic, hypabyssal, and extrusive rocks and related hydrothermal deposits, in complex pegmatites, in carbonatites, and in alteration zones, including greisens, associated with alkalic, silicic, and carbonatite intrusive rocks.

Precambrian plutonic rocks throughout Colorado contain minor fluorite. The Pikes Peak Granite, a massive rock composed of microcline perthite, quartz, and sodic plagioclase, has accessory fluorite in amounts generally less than 1 percent. Similar rocks in northern Colorado locally contain as much as 2 percent disseminated fluorite. Three general types of fluorite are noted: anhedral grains interstitial to or including mafic and felsic minerals; crosscutting veinlets with microcline, sphene, and epidote; and within sericitized feldspar with calcite (G. L. Snyder, personal commun., 1973).

Fluorite, other fluorides, and fluorine-bearing minerals such as tourmaline, topaz, and the micas are common minerals in pegmatites. Fluorite in pegmatites is generally considered a late-stage or hydrothermal-stage mineral. The better known fluorine-bearing pegmatites in the West are Precambrian pegmatites located in Colorado and New Mexico. The Yard pagmatite, Fremont County, Colo., is typical of many of the Colorado pegmatites in that it has a central core composed of pods of milky quartz and crystalline microcline and a wall zone of graphic granite, quartz, microcline, and minor magnetite (Heinrich, 1948, p. 65). Buff-colored fluorite, along with rare-earth minerals and muscovite, occurs as replacement pods along the margin of the core, and purple fluorite, quartz, chlorite, and hematite veinlets cut altered rocks of the wall zone. Fluorite is present in 91 percent of the pegmatites of the Petaca district, New Mexico, as pale-green rounded masses in the wall zone and as deep-purple pods and veinlets throughout (Jahns, 1946, p. 62).

Some fluorite-bearing veinlike deposits, generally of unknown age, probably represent complex pegmatites or hydrothermal deposits derived directly from pegmatites. The scheelite, alkali feldspar, beryl, mica, and fluorite deposits at Oreana, Nev., are generally pegmatitic but grade into fluorite-rich and quartz-rich veins (Kerr, 1946, p.

39). Fluorite-bearing veins at Trout Creek, Utah, composed primarily of carbonate, quartz, mica, and sulfides, are pegmatitic. The Snowbird fluorspar deposit, Montana, contains abundant quartz and carbonate and minor parisite (rare-earth fluorocarbonate), and is thought to be a carbonatite pegmatite (Clabaugh and Sewell, 1964, p. 268). Quartz and the carbonate mineral crystallized from a carbonatite magma and the fluorite and other minerals from a late hydrous solution. The large and very rich fluorspar deposits at Crystal Mountain, Mont., seem to be complex pegmatites. The Crystal Mountain deposits are tabular bodies of fluorite in coarse-grained biotite granite and consist mainly of dark-purple fluorite, but also contain biotite, sphene, quartz, oligoclase, rare-earth-bearing apatite, green amphibole, grains of metamict fergusonite, and the rare scandium mineral thortveitite (Parker and Havens, 1963).

Carbonatite complexes are notably enriched in fluorine which, however, is mostly dispersed through the rock in silicates, apatite, and rare-earth carbonates. Fluorite generally seems to be a late-stage mineral either in the carbonatite, its contact aureole, or in related hydrothermal veins. Carbonatites of the Bearpaw Mountains, Mont., contain about 0.5 percent fluorine in apatite and rare-earth carbonates, fluorite being rare (Pecora, 1962). The Precambrian rare-earth carbonatite at Mountain Pass, Calif., contains about 1 percent fluorine, mostly in the form of bastnaesite, but fluorite forms rare massive pods within small carbonatite veins (Olson and others, 1954). Fluorite is also present in related granites and shonkinitic dikes as a late-magmatic mineral or a postmagmatic alteration mineral. The Goldie carbonatite, Colorado, is mainly limonite-stained calcite with local masses of barite (Heinrich and Dahlem, 1966). Within the carbonatite are replacement nodules of deep-purple fluorite and some alumino fluoride minerals, mainly cryolite. The fluorine minerals are late magmatic or postmagmatic. Fluorite is also a minor constituent in one of four types of related carbonatite dikes found in the area (Parker and Sharp, 1970).

Fluorite, topaz, and apatite are common minerals in contact aureoles around many intrusive bodies, mainly silicic and alkalic rocks and carbonatite complexes. The fluorine minerals occur

in tactite and also in post-tactite hydrothermal veins and replacement bodies. Fluorite is a common constituent of alkalic and silicic-alkalic intrusive bodies in the West and occurs in concentrated amounts, in some places economic, in their contact aureoles. The modes of occurrence are as disseminations within the intrusive rock; veins, stockworks, and mineralized breccias within and surrounding the intrusive body; massive replacement of wall rocks (metasomatic); and disseminations, pods, and stringers in tactites and silicified wall rock.

High fluorine content is a characteristic of most greisens. Quartz-topaz greisens in the central York Mountains, Alaska, are in or near altered biotite granite, and are spatially and genetically related to beryllium-rich fluorite tactite deposits of the Lost River area, Alaska (Sainsbury, 1968). Greisenization consisted of the destruction of feldspar in the granite and the formation of topaz, fluorite, and fluorine-bearing micas along with tin, tungsten, and beryllium minerals. Chemical changes were the loss of K_2O, Na_2O, and SiO_2 and the addition of fluorine, Al_2O_3, total iron, and sulfur along with tin, tungsten, and beryllium. Some of the greisens, as well as unmineralized granite, were later subjected to argillization and sericitization, and in extreme cases were converted to masses of kaolinite with minor fluorite and residual ore minerals (Sainsbury, 1968, p. 1564). Beryllium mineralization near Lake George, Colo., occurred in pipelike and irregular masses of greisen within and along the contact of Precambrian plutonic rocks (Hawley, 1969). The greisens are composed mainly of quartz, muscovite, fluorite, and topaz, with minor pyrite, sphalerite, molybdenite, wolframite, galena, chalcopyrite, bertrandite, arsenopyrite, and sooty pitchblende.

Fluorite and topaz occur in some silicic volcanic rocks of the Western United States, where they are dispersed through the rock and within vugs in the rock (Shawe, 1966, p. C-209). Glass-rich volcanic rocks of silicic composition in the West contain 20 to 4,900 ppm fluorine (Coats and others, 1963). These values may give a rough indication of the fluorine content of the original magma. It must be noted, however, that some fluorine is possibly lost during hydration, and much is lost upon devitrification and alteration to clay minerals (Noble and others, 1967). The high-fluorine glass-rich volcanic rocks are restricted in geographic distribution and are predominantly in a belt in central Colorado and west-central New Mexico, in the Big Bend region of Texas, and in southeastern Idaho, western Utah, and northeastern Nevada (Coats and others, 1963, p. 941).

Some fluorine occurrences in sedimentary rocks appear to be genetically related to the enclosing sediments, but many may be of hydrothermal or metasomatic origin. Fluorine minerals occur in volcaniclastic sedimentary rocks, lacustrine deposits, and marine carbonate and marine phosphate rocks. In general, economic concentrations of fluorine minerals do not occur in detrital accumulations.

Although volcanic ash commonly contains fluorine in glass shards and adsorbed on tephra, commercial or potential deposits of fluorine in volcaniclastic sedimentary rocks appear to be either interbedded deposits of lacustrine origin or disseminated deposits of probable hydrothermal origin (for example, Spor Mountain, Utah, described later in this report). Fluorite-bearing lacustrine deposits near Rome, Oreg., are interbedded with volcaniclastic sediments. Here fluorite occurs as submicroscopic, nearly spherical grains in tuff, tuffaceous mudstone, and mudstone of Tertiary lacustrine deposits (Sheppard and Gude, 1969). Fluorite is nonuniformly distributed through about 60 feet of section, but occurs in abundance (as much as 16 percent) in one conspicuous zeolitic tuff. The rocks do not appear to have been hydrothermally altered. Zeolites, clay minerals, quartz, potassium feldspar, and calcite making up the tuffaceous parts of the fluorine-bearing rocks seem to be the result of reaction between silicic shards and crystal fragments and saline and alkaline pore water during diagenesis. Most constituents of the mudstone are detrital. The depositional environment for these rocks must have been saline and alkaline, and also at some time enriched in fluorine, such as waters of some present-day lakes in the rift valleys of Africa (Sheppard and Gude, 1969, p. D72). The fluorine may have been deposited originally as villiaumite (NaF), an evaporite mineral which was later changed to fluorite by calcium-bearing water that infiltrated the lacustrine rocks after deposition. In any case, the fluorite was authigenic.

Marine carbonates and evaporites in the U.S.S.R. contain as much as 30 percent fluorite as fine disseminations and crystal aggregates. According to experimental data (Kazakov and Sokolova, 1950), the fluorite probably formed as a precipitate from sea water that had been concentrated three or four times. Similar deposits in the Western United States may be present in the Bighorn Mountains, Wyo., where dolomitic limestone containing 12 to 15 percent fluorite has been recorded (Gulbrandsen and Reeser, 1969, p. C55). Fluorite in the Pennsylvanian and Permian Minnelusa Formation near Custer, S. Dak., occurs as minute crystals in vugs, and as masses within gypsum patches in dolomite (Roberts and Rapp, 1965, p. 87). In the same area the Permian Minnekahta Limestone, a thinly laminated pink to red anhydritic limestone, contains purple fluorite as subhedral grains, 0.1 to 0.25 mm in diameter, along certain laminae. The fluorite grains are surrounded by fine-grained calcite or are within gypsum crystals.

The ore mineral of sedimentary phosphate rock is carbonate-fluorapatite with ratio of F to P_2O_5 about 1 to 10. Phosphate rock contains as much as 4 percent F and 40 percent P_2O_5, although lower grade deposits are now mined for their phosphate content. Fluorite is common in minor amounts in these deposits and occurs within and among the carbonate-fluorapatite pellets. Other minor components present are zircon, tourmaline, rare metals, and the rare earths. Fluorite in the phosphorites is secondary and apparently the product of a diagenetic reorganization of carbonate-fluorapatite (Gulbrandsen and Reeser, 1969).

Topaz and tourmaline are common in metamorphic rocks, and in places where abundant they may represent future sources of fluorine. For example, a Precambrian topaz-quartz-sillimanite gneiss in the central part of the Front Range, Colo., contains major amounts of topaz (Sheridan and others, 1968). This unit, part of a high-grade metamorphic gneiss and granitic plutonic complex, is 11 to 100 feet thick and crops out along strike for 7,000 feet. Three composite chip samples of this unit were found to contain 67, 23, and 3.6 weight percent topaz and 4.2, 3.9, and 2.2 weight percent rutile. The gneiss may warrant investigation as an ore of rutile, especially since it might also yield topaz or topaz and sillimanite as byproducts (Sheridan and others, 1968).

Fluorite-bearing hydrothermal deposits are abundant in the Western United States (Figs. 1, 2, and 3) and represent much of the past and future fluorspar resources. Fluorite is generally the only fluorine mineral present and its abundance ranges from nearly 100 percent down to trace amounts. Hydrothermal fluorite occurs in many types of host rock, but is especially common in sedimentary carbonate, silicic igneous, and silicic metamorphic rocks. Form is the standard basis of classification and in general hydrothermal fluorspar deposits can be grouped into veins, mantos, pipelike bodies and stockworks, and disseminated deposits. Most commercial fluorspar deposits in the West have been hydrothermal veins, many with associated mantos, pipelike bodies, and stockworks. Disseminations of fluorite are common in hot springs deposits and in large masses of hydrothermally altered rock.

GEOLOGY AND GEOCHEMISTRY OF TERTIARY LATE-MAGMATIC AND HYDROTHERMAL FLUORITE

Most known fluorspar deposits and fluorite occurrences in the West are late-magmatic and hydrothermal deposits of Tertiary age; exceptions are fluorite in pegmatites, carbonatites, sedimentary rocks, and Precambrian batholithic rocks. This section deals exclusively with the Tertiary late-magmatic and hydrothermal fluorite occurrences and fluorspar deposits. The others are discussed in the section on geologic environment of fluorine. Tertiary fluorite in the West occurs in deposits of many forms, including veins, pods, mantos, pipelike bodies, stockworks, disseminations, and irregular fine-grained replacement (metasomatic) bodies, and it formed in a great diversity of environments by deposition from a variety of solutions.

The amount of fluorite present ranges from nearly 100 percent down to trace amounts. A very basic, but debatable, assumption is made in this report that the major difference between the Tertiary group classed as fluorite occurrences and that classed as fluorspar deposits is the relative abundance of the constituents. The two are very similar in distribution (Figs. 1, 2, and 3), age, mineralogy, geochemistry, alteration types, igne-

ous associations, and geologic settings. In detail, however, many subtle differences between fluorspar deposits and fluorite occurrences probably exist which, when defined, may be important exploration and evaluation guides.

For the purpose of discussion, Tertiary fluorspar deposits and fluorite occurrences have been subdivided into two general types: those deposits within or associated with intrusive igneous rocks and those deposits not associated with intrusive igneous rocks (hot-spring, epithermal, and volcanic types). In this evaluation small hypabyssal igneous bodies such as dikes and sills are not considered as associated intrusive rocks because, although genetically related, they do not represent the source of the ore-forming solution. This is an arbitrary breakdown but serves the purpose well to illustrate the general range of conditions under which fluorite formed. A complete gradation exists between the two types, and some deposits and districts exhibit characteristics of both.

The geologic and geochemical characteristics of each type are summarized in Table 1. Note the similarities in geochemistry, mineralogy, alteration types, and igneous associations. Differences in mineralogy, texture, and nature of the ore-forming solutions reflect differences in environment of deposition. Differences in age reflect the depth of exposure; the older deposits expose a relatively deeper environment of deposition. Although diverse in some aspects, the many aspects in common among all Tertiary fluorite-bearing deposits suggest that they all formed from a similar magmatic-hydrothermal system, each individual deposit representing one segment of that system (Worl, 1971). This does not imply a single source for the water or for many of the other constituents, as it is apparent that fluorite and related minerals were deposited from waters that were dominantly either magmatic, connate, or meteoric. It does imply, however, that most of the fluorine present in these deposits had an ultimate deep-seated source. In general all Tertiary fluorite-bearing hydrothermal deposits formed from similar magmatic-hydrothermal systems characterized by a restricted group of associated elements, alteration types, and related igneous activity (see Table 1). The deposits associated with intrusive rocks represent deposition from this system at depth, and those deposits not associated with intrusive rocks represent deposition from this system at or near the surface.

Fluorite Associated with Intrusive Igneous Rocks

Examples of fluorspar deposits and fluorite occurrences of this type occur throughout the fluorine-rich areas of the West (Fig. 1) but are not nearly as common as those deposits not associated with igneous intrusive rocks (Figs. 2 and 3). Fluorite related to intrusive rocks (not including hypabyssal dikes and sills) occurs within the intrusive, its contact aureole, or in close proximity to the intrusive, and is genetically related to at least part of the intrusive complex. The modes of occurrence are as disseminations in the intrusive rock; veins, stockworks of veinlets, and mineralized breccia zones within and surrounding the intrusive; pods and stringers in skarns and tactites; and irregularly shaped fine-grained replacement bodies (metasomatic).

Alkalic rocks in many small Tertiary intrusive bodies contain fluorite as an accessory mineral. A small stock of silicic-alkalic composition associated with fluorspar deposits of the Jamestown district, Colorado, contains as much as 4 percent fluorite as interstitial grains and in veinlets with chalcedonic quartz, molybdenite, and potassium feldspar. In the Little Rocky Mountains, Mont., fluorite is sparsely disseminated throughout a porphyritic syenite and makes up 2 to 3 percent of the rock; it also occurs with quartz and tellurides in highly mineralized breccias within the syenite (Sahinen, 1962, p. 34). Fluorite occurs as disseminated grains and as replacements of previously altered plagioclase along minute fractures in an intrusive leucorhyolite in the South Moccasin Mountains, Mont. (Sahinen, 1962, p. 32). Fluorite is also a constituent of hydrothermal deposits and alteration zones in sedimentary rocks surrounding the intrusive. Fluorite in the three intrusives discussed here, as in most studied, seems to be a late-magmatic or post-magmatic alteration mineral.

Fluorite in the Gallinas Mountains, N. Mex., occurs in irregular breccia zones, pipelike breccia bodies, and fissure veins in quartzitic sandstone next to alkalic intrusives. The breccia zones range in width from a few inches to as much as 30 feet and in length from a few feet to many tens of feet (as much as 600 feet in one place)

Table 1.—Characteristics of Fluorite Associated With Intrusive Igneous Rocks Compared With Those of Fluorite Not Associated With Igneous Rocks

CHARACTERISTICS	FLUORITE ASSOCIATED WITH INTRUSIVE IGNEOUS ROCKS		FLUORITE NOT ASSOCIATED WITH INTRUSIVE IGNEOUS ROCKS	
TYPES OF DEPOSITS	Tactites Breccia pipes	Stockworks Disseminated	Veins Mantos	Pipelike bodies Disseminated
MINERALOGY	Calcite Barite Quartz Rhodochrosite	Potassium-bearing minerals common in both altered and mineralized rock	Calcite Barite Chalcedony Manganese oxides	Iron oxides Celestite Potassium feldspar
TEXTURE	Crystalline aggregates Breccias Corroded crystals common		Banded Crustified Reniform Mammillary	Breccias, water courses, and vugs common
FLUORITE	Coarsely crystalline, commonly containing trace metals Fine-grained massive		Columnar, rarely containing trace metals Porcelaneous Earthy	Fine mixture of fluorite, chalcedonic quartz, pyrite, jarosite, biotite, sericite, or feldspar. Contains trace metals
ALTERATION	Silicic Feldspathic	Argillic	Silicic, very common Feldspathic, argillic, sericitic, minor	
PARAGENESIS	Deposition consisted of a few polymineralogic stages		Deposition consisted of many monomineralogic stages, and a few polymineralogic stages (earthy and porcelaneous fluorspar)	
ASSOCIATED METALS	Ag, Au, Ba, Be, Fe, Mn, Mo, Pb, Sn, Te, U, W, and Zn		Ag, Au, Ba, Be, Fe, Li, Mn, Mo, Pb, Sr, Sn, Te, U, V, and Zn	
IGNEOUS ASSOCIATION	Alkalic (K-rich) and silicic-alkalic intrusive complexes		Mainly no igneous association; a few with hypabyssal bodies and flows of bassalt and rhyolite	
AGE	30 to 20 m.y. before present; some older in California, Nevada, and Utah		Post-20 m.y. and pre-6 m.y. before present	
TEMPERATURE OF FORMATION	150°C to 500(?)°C (maximum)		75°C(?) to 250°C	
NATURE OF ORE-FORMING SOLUTION	Ascending, variable, and complex; generally saline		Ascending and convective; generally dilute	
STRUCTURAL CONTROL			Major tensional faults, Rio Grande rift system, Basin and Range faults	

(Perhac, 1970, p. 41). The extensive fluorspar deposits at Jamestown, Colo., are in breccia veins and breccia zones that radiate from a small silicic-alkalic intrusive body. The larger and higher grade fluorspar deposits are lenticular pipelike bodies, 10 to 100 feet wide, as much as 500 feet long, and at least 1,400 feet deep, within the major breccia zones. The average grade of ore produced from the breccia deposits at Jamestown is about 50 percent CaF_2, although many high-grade pockets containing 75 to 95 percent CaF_2 have been mined. The silica content is high, 10 to 40 percent, but is easily removed because the fluorite is not intimately intergrown with the silica (God-

dard, 1946, p. 20). Most of the silica is present in the form of feldspar and quartz in wall-rock fragments. Some of the flourspar deposits in the Star Range, Utah, are in a large-scale stockwork within and surrounding a silicic intrusive.

Abundant fluorite is present in an iron-rich tactite formed by replacement of Paleozoic limestone at the contacts with small intrusive bodies of granite, rhyolite, and aplite at Iron Mountain, N. Mex. The tactite is mainly coarsely crystalline magnetite, andradite garnet, hedenbergite, and hematite. Fluorite, apatite, scheelite, and sulfides are later than the major rock-forming minerals. Most of the fluorite is crystalline and is interlayered with magnetite, specular hematite and silicates in masses of "ribbon rock" in the form of thick pods, pipelike bodies, and thin tabular bodies in earlier formed tactite (Jahns, 1944, p. 55). Fluorite is sufficiently abundant here to warrant investigations as a resource. At the Tootsie Creek deposits, Sweetgrass Hill, Mont., fluorspar is present as irregular pods and fine-grained replacement seams in or adjacent to marbleized Madison Limestone in the contact zone of an intrusive alkalic syenite (Ross, 1950). The Tootsie Creek fluorspar bodies are generally small, the largest being 10 feet wide and 50 feet long, but are scattered throughout an area 2,000 feet long and several hundred feet wide. The average grade of typical better ore is about 50 percent CaF_2 and 30 percent silica (Ross, 1950, p. 196). Removal of the silica from this ore would require very fine grinding because much of it is intimately intergrown with the fluorite.

Fluorite occurrences associated with intrusive igneous rocks include the fluorite in stockworks and alteration zones associated with molybdenum deposits at Climax, Colo. (Wallace and others, 1968) and Questa, N. Mex. (Carpenter, 1968); fluorite in tungsten skarns at Tem Piute, Nev. (Buseck, 1967) and the Bishop district, California (Gray and others, 1968); fluorite with gold tellurides as a stockwork of veinlets in the Little Rocky Mountains, Mont. (Sahinen, 1962); fluorite in tungsten- and beryllium-bearing pyrometasomatic skarn deposits in the Victorio district, New Mexico (Warner and others, 1959, p. 122); fluorite in iron-rich contact-metamorphic deposits of the Alder Creek district, Idaho (Umpleby, 1917); fluorite in lead and zinc sulfide-rich contact-metamorphic deposits of the Alta district, Idaho (Umpleby and others, 1930); and fluorite in contact aureole quartz veins of the Blue Wing district, Idaho, with orthoclase, rhodochrosite, huebnerite, pyrite, molybdenite, and tetrahedrite (Anderson and Van Alstine, 1964).

Fluorite associated with intrusive igneous rocks is generally either in coarsely crystalline aggregates with other minerals or in very fine-grained massive material which is a replacement of calcareous sedimentary rocks (metasomatic). Corroded crystals and replacement textures are common. Sugary-textured fluorspar (sugar spar) at Jamestown, Colo., Gallinas Mountains, N. Mex., Judith Mountains, Mont., and elsewhere is composed of highly corroded and rounded grains of fluorite set in a matrix of clay minerals, sericite, and fluorite. Very fine-grained intimate intergrowths of fluorite and other constituents, mainly silica, are confined to the fine-grained massive replacement (metasomatic) deposits.

Hydrothermal alteration consisted of several types characterized by the development of muscovite, sericite, potassium feldspar, biotite, albite, pyrite, fluorite, clay minerals, and fine-grained silica. Hydrothermal alteration was in addition to, and commonly imposed upon, contact metamorphism that had already taken place. Alteration around fluorite occurrences of this type has been well studied in some districts such as Climax, Colo. (Wallace and others, 1968), Questa, N. Mex. (Carpenter, 1968), and Bishop, Calif. (Gray and others, 1968). However, the alteration effects around fluorspar deposits of this type have not been studied in detail. In general it seems that clay minerals, biotite, sericite, and secondary feldspars are the common alteration products within and around the larger coarse-grained bodies of fluorspar, while silicification and pyritization were more prevalent within the intrusive rock and along smaller veins and stockworks away from the larger bodies. Silicification seems to have been common in many fine-grained replacement (metasomatic) fluorspar bodies as it was in the deposits in Brewster County, Tex. (McAnulty, 1967).

Common associated minerals in the fluorspar deposits are calcite, quartz, barite, rhodochrosite, biotite, potassium feldspar, molybdenite, galena, sphalerite, and pyrite. Associated elements com-

mon in both fluorspar deposits and fluorite occurrences include silver, gold, barium, beryllium, iron, manganese, molybdenum, lead, the rare earths, tin, tellurium, uranium, tungsten, and zinc. The extent and reliability of the relationship between fluorite and some of these elements is so well established that fluorite is ofen used as an exploration guide for those elements. The genetic relationship of fluorite to some of the other elements is sporadic and questionable. Most gold telluride deposits and many, but not all, gold-quartz deposits contain abundant fluorite gangue. Many, but not all, tungsten-rich tactites and skarns contain generally minor amounts of fluorite as do many iron-rich tactites. Most uranium mineral deposits in the intrusive environment have minor fluorite gangue as do similar deposits containing the rare earths, tin, and beryllium. Many, but not all, lead-silver deposits in the intrusive environment contain fluorite. Almost all molybdenum deposits of this type, both stockwork and contact metamorphic, contain abundant fluorite gangue. These same deposits may have anomalous concentrations of manganese and barium. Fluorspar deposits contain many of the elements listed, locally in possible economic proportions, but commonly in trace amounts only.

All fluorite analyzed from the Western States contained trace amounts of barium, manganese, strontium, and yttrium. Gold telluride deposits in the Sweetgrass Hills, South Moccasin Mountains, and Judith Mountains, Mont., have abundant purple fluorite gangue, and the nearby and genetically related fluorspar deposits carry trace amounts of gold (Sahinen, 1962, p. 26). Fluorspar deposits in the Chinati Mountains, Tex., are fluorite-lead-zinc-silver-gold veins in jointed or sheeted zones within, and presumably related to, a laccolithic intrusive (McAnulty, 1972a). Contact-metamorphic lead-zinc deposits in the Star Range, Utah, contain abundant fluorite gangue, and related fluorspar deposits are locally rich in sulfides (Thurston and others, 1954, p. 19). Possible commercial amounts of fluorite occur in iron-rich tactites at Iron Mountain, N. Mex., the Alder Creek district, Idaho, and in the Blawn Mountain area, Utah (Whelan, 1965). Fluorite in molybdenum porphyries or stockworks is generally related to an alteration phase that formed above

and away from the main molybdenum mineralization or is a later stage of the same episode of mineralization. However, enough fluorite was deposited with the molybdenum mineralization in some areas to warrant investigation as a possible byproduct. Fluorspar deposits in the Gallinas Mountains, N. Mex., contain bastnaesite (rare-earth fluorcarbonate) in nearly commercial quantities. These same deposits have been worked in the past for lead-silver, gold, and copper; this example is a rare instance of copper mineralization associated with fluorite. Fluorspar deposits at Jamestown, Colo., have been worked for lead-silver and gold. A late-stage solution in the fluorite mineralization at Jamestown also introduced anomalous amounts of beryllium, lanthanum, molybdenum, vanadium, uranium, scandium, and the rare earths. In deposits of this type, many of the metals are restricted in their mineralogy; sulfides are dominant, gold is commonly in tellurides, iron in pyrite or magnetite, manganese in carbonates or silicates, and uranium in pitchblende.

Lindgren (1933, p. 153) noted the frequent association of fluorite with intrusive rocks of alkalic type, but offered no explanation of the significance of the numerous alkalic intrusive centers that do not have related fluorite. Indeed, most of the intrusive bodies directly related to fluorspar deposits—the Sweetgrass Hills and Judith Mountains, Mont. (Sahinen, 1962, p. 26); Bear Lodge Mountains, Wyo., Jamestown district, Colorado (Goddard, 1946); Gallinas Mountains, N. Mex. (Perhac, 1970); and Eagle Mountains (Gillerman, 1953) and Christmas Mountains (McAnulty, 1967), Tex. —are alkalic at least in part. These intrusives, plus many others related to fluorite occurrences, have one aspect in common: the crystallization stage genetically related to the fluorite mineralization and alteration was late in the magmatic sequence. This stage was generally alkalic in nature and in some cases was superimposed upon silicic and silicic-alkalic rocks of earlier stages. It is difficult to distinguish between products of late-magmatic alkalic activity and post-magmatic hydrothermal activity, but much of the fluorite seems to be post magmatic and hydrothermal. Still, the amount of fluorite in the deposit does have a direct relationship to the presence and amount of late-magmatic alkalic activity.

Many of the intrusive bodies with related fluorite occurrences have been radiometrically dated. The intrusives at Climax, Colo. (Wallace and others, 1968); Questa, N. Mex. (Carpenter, 1968); Magdalena, N. Mex. (Kottlowski and others, 1968); Organ Mountains, N. Mex. (Kottlowski and others, 1969); and Gallinas Mountains, N. Mex. (Perhac, 1970) have radiometric dates that fall between 30 and 22 million years before the present. Unpublished dates from a few alkalic intrusives related to fluorspar deposits indicate that they also fall into this general range of ages. Some intrusive igneous rocks and related fluorite occurrences in California, Nevada, and Utah are probably older, but are generally of unknown age.

The ore-forming solutions were generally complex and variable, in some stages or places dense and hot and in other stages or places dilute and cool; the solutions were in part magmatic, in part pneumatolytic, and in part hydrothermal. The paragenetic sequence of several deposits suggests relatively few stages of deposition, with each stage depositing several minerals nearly simultaneously. In the Bishop tungsten district, California, the earlier ore-forming solutions were pneumatolytic and formed calc-silicates, fluorite, scheelite, and quartz, whereas later solutions were hydrothermal and deposited base-metal sulfides, pyrrhotite, sericite, biotite, quartz, pyrite, molybdenite, and fluorite (Gray and others, 1968). Fluorspar deposits in the Gallinas Mountains, N. Mex., were deposited in two hydrothermal stages; fluorite is not present in earlier iron-rich contact-metasomatic deposits. The first hydrothermal stage deposited quartz, barite, sulfide minerals, fluorite, bastnaesite, and minor calcite; the second stage, following local fracturing, deposited barite, fluorite, local calcite, and minor chalcedony. Studies of the fluid inclusions in bastnaesite indicate depositional temperatures of 175° to 185°C (Perhac, 1970, p. 46). At Tem Piute, Nev., fluorite, along with base-metal sulfides and quartz, occurs in the outer part of a garnet-pyroxene skarn, whereas minerals in the inner zone consist of pyrrhotite, magnetite, and molybdenite. Scheelite and pyrite occur throughout. Rough estimations of the temperature of deposition are as much as 500°C for the inner zone and about 200°C for the outer zone (Buseck, 1967, p. 347). Fluorite at James-

town, Colo., was deposited during two of the three major depositional stages (J. T. Nash and C. G. Cunningham, oral commun., 1972). The first stage deposited quartz and sulfide minerals from a hot and relatively saline (26 weight percent) fluid. The second stage was major fluorite deposition from a complex and variable solution. Temperatures ranged from 275° to 375°C; salinities generally ranged from 26 to 32 weight percent although in a few places they were as high as 40 weight percent, and the CO_2 content ranged from very high to low. The final stage was a relatively cool (about 250°C) and dilute (less than 26 weight percent) fluid which corroded the existing fluorite, deposited clay minerals, sericite, biotite, sulfides, and fluorite, and introduced anomalous amounts of gold, beryllium, lanthanum, molybdenum, scandium, vanadium, uranium, cesium, and neodymium.

Fluorite Not Associated With Intrusive Igneous Rocks

Fluorite not associated with intrusive igneous rocks is the most abundant and commercially most important type of fluorite in the West. Fluorspar deposits of this type have commonly been termed hot-springs type, epithermal, or banded. Some fluorite of this type is within or related to minor hypabyssal dikes and sills or extrusive igneous rocks, but much is isolated from any associated igneous rocks. The modes of occurrence are veins, mantos, irregular breccia deposits, pipelike bodies, disseminations, and coatings in recent hot-springs deposits, and as disseminations through altered rock.

Veins are the most common. Fluorspar deposits in the Northgate district, Colorado, consist of two large parallel veins in Precambrian rocks about 2 miles apart. One vein system is mineralized for a length of about 1 mile, and the other for a length of over 2 miles, although sparsely in places. Fluorite occurs throughout a known vertical range of more than 1,000 feet. Fluorspar-bearing brecciated fault zones as much as 70 feet wide are common, as are fluorspar ore-grade zones 20 feet wide. The CaF_2 content of zones 8 to 11 feet wide ranged from 10 to 90 percent and averaged 40 to 50 percent (Steven, 1960, p. 399). Fluorspar deposits at the Baxter mine, Broken Hills district, Nevada, occur along a single but bifurcating fault

zone in altered Tertiary volcanic rocks. Fluorspar did not extend far below the 700-foot level of the mine, and along much of the vein system it did not extend below the 400-foot level; the ore zones narrowed with depth. Before 1951, production averaged 85 percent CaF_2 and after 1951 it averaged 46 percent CaF_2. This deposit was reported as exhausted in 1957 (Matson and Trengove, 1957). Within the Zuni Mountains, N. Mex., an elongate dome of Precambrian rocks, there is a mineralized zone 20 miles long and 3 miles wide that contains hundreds of steeply dipping fluorspar veins ranging in length from a few feet to almost a mile and in width from a few inches to 15 feet. The ore bodies mined to date have been 15 inches to 6 feet wide in most places, but locally they have been as much as 15 feet. The two major producing mines have been explored to depths of 700 and 380 feet. These veins contain as much as 95 percent CaF_2, but the ore shipped from the mines has ranged from 17 to 86 percent CaF_2. A mill head of 40 percent CaF_2 was maintained (Goddard, 1966). The Browns Canyon district, Colorado, contains several veins, one that has been mined for 1,600 feet in length. The veins at Browns Canyon range in size from lenses tens of feet long and inches thick to sheeted zones 1,000 feet long and 25 feet thick. The average mining thickness was less than 10 feet. Mined bodies ranged in grade from less than 25 percent CaF_2 to as much as 75 percent, with some large areas containing 50 to 55 percent (Van Alstine, 1969, p. 37).

Many fluorspar districts have numerous veins of insufficient size to warrant exploitation. The White Signal and Gold Hill districts and the Soldiers Farewell Mountain area, western Grant County, N. Mex., contain numerous small high-grade fluorspar veins along major graben faults, but none is of sufficient size to warrant extensive development. Most are no more than 100 feet in length and 2 feet in width, although these lenses in one place are scattered along a fault zone for a length of 3,200 feet and are almost pure fluorite with minor quartz and sulfides (Gillerman, 1952). In one part of the Cooks Peak district, New Mexico, hundreds of small irregular lenses and pods of fluorspar are scattered over a surface area of about 80 acres. These lenses, as much as a few

tens of feet in length, occur in diffuse breccia zones in volcanic rocks (Williams, 1966, p. 34).

Manto deposits are not as common in the Western United States as they are farther south in Mexico. The known mantos are generally small or of low grade and have not been major producers. Deposits in the Quinn Canyon Range, Nev., occur in a variety of forms. In limestone country rock the deposits occur as small replacement bodies that extend from rhyolite dikes and as large irregular replacement bodies and breccia fillings that extend from fault zones and rhyolite dikes. The CaF_2 content ranges from 16 to more than 90 percent, but the silica content is as much as 74 percent in some zones and averages high throughout (Sainsbury and Kleinhampl, 1969, p. C7). Fluorspar, barite, and lead deposits in the Hansonburg district, New Mexico, occur along northward-trending faults in the form of lenticular and blanketlike replacement bodies. The individual deposits extend from the faults for distances of generally less than 50 feet, but extend along the faults as much as 300 feet (Roedder and others, 1968, p. 336). At Bishop Cap Hills, N. Mex., much of the fluorite, barite, calcite, and minor sulfide mineralization formed pods, stringers, veins, and cavity fillings in silicified fault and breccia zones in fractured limestone. Mineralization was not confined to fractured rock, however, as some limestone units were extensively silicified and mineralized with fluorite, barite, pyrite, siderite, and calcite for some distance away from faults. Some zones are radioactive and others contain as much as 150 ppm silver. These mineralized zones seldom exceed a few feet in thickness and the CaF_2 content is generally low (Kramer, 1970). At the Wells Cargo deposit, Lincoln County, Nev. (Horton, 1961, p. 13), most fluorite is in veins and stringers along fault zones, but some occurs as massive crystalline pods extending outward from the veins into the limestone country rock; in a few places fine-grained gray fluorite, similar in color and texture to the country rock, has replaced the country rock for unknown distances away from the faults.

Many districts contain pipelike fluorspar bodies localized along faults or fissure veins. Excellent examples occur in the Thomas Range, Utah, and the Fluorine district, Nevada (Peters, 1958, p. 672). In the Daisy mine, Fluorine district, Nevada,

the fluorspar deposits occur as veins and irregular steeply dipping pipelike lenses in highly deformed and fractured dolomite or limestone near major faults (Cornwall and Kleinhampl, 1964, p. J19). The size of the pipelike bodies varies greatly, from pods 20 feet across to masses 350 feet long, with minable widths as much as 65 feet (Thurston, 1944). The ore mined through 1961 averaged about 75 percent CaF_2 with less than 2 percent silica (Cornwall and Kleinhampl, 1964, p. J21). Pipelike fluorspar bodies in the Thomas Range, Utah, are oval to irregular in shape and tend to narrow with depth. Deepest mining has been about 200 feet below the surface. The pipelike bodies range in size from pods less than 1 foot in diameter to masses 155 feet long by 106 feet wide. The ore ranges in grade from 65 to 95 percent CaF_2, but it is generally siliceous. Mine shipments during 1944-56 averaged 72 to 82 percent CaF_2 (Staatz and Carr, 1964, p. 143).

Small amounts of fluorite occur as disseminations in travertine deposits of some recent hot springs. A travertine deposit, some 500 feet above the present hot springs at Ojo Caliente, N. Mex., contains nearly 1 percent CaF_2 (White, 1955). Small fluorite veins occur along the same fault structure and just above the present springs. Fluorite-bearing travertine, formed from thermal waters at Poncha Springs, Colo., consists of about 95 percent calcite with minor amounts of manganese oxide, chalcedonic quartz, opal, quartz, chlorite, muscovite, and fluorite (Van Alstine, 1969, p. 35).

Fluorite and minor tourmaline occur in argillized rocks associated with uranium deposits in the Marysvale district, Utah (Kerr and others, 1957). During progressive stages of alteration, fluorite first formed as veinlets when kaolinite and montmorillonite became the major alteration products and the previously resistant orthoclase became partly sericitized; fluorite continued to be formed during alteration to a rock composed mainly of fine-grained (in part recrystallized) quartz and sericite, with kaolinite, illite, pitchblende, pyrite, and black fluorite. Fluorite in the less altered rocks tends to be green or clear in color but is dark purple to black in the highly altered rocks and veins. Fluorite is a minor constituent of hydrothermally altered rocks in the South Moccasin Mountains, Mont. (Sahinen, 1962,

p. 30). Brecciated zones and permeable strata of sandstone have been kaolinized, some completely, to compact masses of clay with minor amounts of magnetite, pyrite, sericite, fluorite, orpiment, realgar, gypsum, and opaline quartz.

In many areas, intensely silicified rocks contain dispersed fluorite. These rocks include jasperoid (silicified limestone) and jasperized igneous rock in which most of the fluorite is erratically distributed in vugs, fractures, and breccias. Some fluorite, along with chalcedonic quartz, occurs as a fine-grained replacement of wall-rock fragments.

Although fluorspar in hydrothermal alteration zones tends to be low grade and irregularly dispersed, some areas of silicified rock may contain commercial concentrations of fluorine (McAnulty, 1972b). Bulk samples of jasperoid (silicified limestone) mined for fluorspar content in the Winkler anticline, New Mexico, averaged 33.42 percent CaF_2 (McAnulty, 1972b, p. 2). In the Quinn Canyon Range, Nev., small pods, stringers, and veinlets of fluorite in large tabular bodies of brecciated and silicified volcanic rocks are being exploited (Sainsbury and Kleinhampl, 1969, p. C18). The Grand Reef, Aravaipa district, Arizona (Ross, 1925, p. 59), is a zone several miles long and a few hundred feet wide of intensely brecciated and silicified rock, chiefly in intrusive rhyolite. Mineralization consisted mainly of the formation of veins, stringers, and irregular pods of quartz, fluorite, and sulfides within the silicified zones. More importantly, fluorite is also present as a very fine intergrowth with chalcedonic quartz in a rock that resembles chert or jasperized rock; fluorite is detectable by X-ray diffraction analysis only.

In the Western United States many areas of hydrothermally altered volcanic rock, agglomerates, volcaniclastic sediments, and unconsolidated clastic sediments contain dispersed fluorite. The fluorite-beryllium deposits near Spor Mountain and the Honeycomb Hills, Utah, are good examples (McAnulty and Levinson, 1964). Altered water-laid tuff near Spor Mountain, Utah, contains commercial amounts of beryllium and about 4 percent CaF_2. Microscopic fluorite is dispersed through altered tuff and in a fine-grained intergrowth with opal and chalcedony in nodules as much as 30 cm in diameter. Although some flu-

orite in these deposits may have been derived from leaching of fluorine from the included volcanic ash, most of the fluorine along with beryllium, lithium, manganese, uranium, and trace amounts of niobium, cesium, and yttrium, was introduced by laterally spreading hydrothermal solutions (Staatz and Griffitts, 1961; Lindsey and others, 1973).

Fluorite occurrences not related to intrusive igneous rocks are numerous and most are listed in Anderson and Van Alstine (1964), Dasch (1964), Geach (1963), Horton (1961), Thurston and others (1954), Van Alstine and Moore (1969), and Van Alstine (1964, 1965, and 1966). Good examples are the fluorite gangue in gold telluride deposits of Cripple Creek, Colo.; gold-quartz veins at Jarbridge, Nev.; barite deposits at Rowley, Ariz.; beryllium deposits at Spor Mountain, Utah; manganese deposits of the Luis Lopez district, New Mexico; lead-silver veins of the Castle Dome lead mine, Arizona; molybdenum-lead-manganese-silver veins of the Trigo Mountains, Ariz.; and the uranium deposits at Marysvale, Utah.

Fluorite not related to intrusive igneous rocks is generally columnar in habit, massive porcelaneous, or in earthy masses. Columnar fluorite is made up of acicular fibers or massive columns of fluorite generally perpendicular to vein walls or radiating from fragments (Peters, 1958, p. 672). The porcelaneous and earthy varieties are actually a very fine grained mixture of fluorite, chalcedonic quartz, and commonly pyrite, jarosite, biotite, sericite, clay minerals, and feldspar. Monomineralogic layering, with crustiform and mammilary textures, is common, as are massive fine-grained, essentially featureless masses. Water courses and vugs are common, as are pseudomorphs of fluorite after calcite and other minerals.

Hydrothermal alteration in and around fluorspar deposits not related to intrusive igneous rocks varies greatly in degree; in some areas the wall rocks are little altered, or not at all, but in other areas they are extensively altered. Many small fluorspar veins like those in the Soldiers Farewell Mountain, Redrock, and El Rito areas, New Mexico, have had no associated alteration; the wall rocks next to fluorite in the fissures are unaltered. Silification is the predominant type of alteration associated with fluorspar deposits. Pyritization, sericitization, and feldspathization were common in some districts and argillization of feldspars occurred in a few. In the Zuni Mountains, N. Mex., mild silicification occurred in zones ranging in width from 1 inch along some fluorspar veins to 1,000 feet along several others (Goddard, 1966). Wall-rock alteration, mainly silicification and fluoritization, was not extensive in the Browns Canyon district, Colorado, and extended no more than several inches on either side of the vein (Van Alstine, 1969). Material within the breccia pipes in the Thomas Range, Utah, is silicified and argillized, but the wall rocks adjacent to the pipes are unaltered. Alteration in the Northgate district, Colorado, consisted of a zone of mild silicification, pyritization, and fluoritization in the form of a very fine-textured and pervasive network of veinlets composed of chalcedonic quartz, fluorite, pyrite, and occasionally molybdenite centered on the fluorspar vein (Worl, in U.S. Geological Survey, 1970, p. A5). Massive silicification was common in some areas (McAnulty, 1972b) and covered a much larger area than the related fluorite deposits. (See discussion of fluorite in alteration zones in previous section.) Alteration types, other than silicification, are generally not extensive, although fluorspar deposits in the Clark Mountains, Calif., consist of fluorite disseminated through highly sericitized dolomite (Crosby and Hoffman, 1951), and fluorite in the Marysvale, Utah, district is in veins and disseminations in highly argillized volcanic rocks.

Commonly associated minerals in fluorspar deposits not associated with intrusive igneous rocks are calcite, chalcedonic quartz, barite, celestite, potassium feldspar, hypogene iron, and manganese oxides; less common minerals are jarosite, wulfenite, galena, pyrite, and secondary uranium minerals. Associated elements are silver, gold, barium, beryllium, iron, lithium, manganese, molybdenum, lead, strontium, tellurium, uranium, vanadium, and zinc. As with the other type of Tertiary fluorite deposits, association with some elements is quite strong, whereas it is somewhat questionable with others. Examples of fluorite gangue in metal deposits have already been listed. Nearly all gold, barite, beryllium, molybdenum, and lead-zinc-silver deposits not associated with intrusive igneous rocks have fluorite gangue, commonly in abundance. Most hypogene manganese and iron oxide deposits contain minor amounts of

fluorite (Hewett, 1964). Fluorite is a local gangue mineral in the Terlingua mercury district, Texas, and cinnabar is a minor constituent of fluorspar in the Fluorine district, Nevada; however, mercury and fluorite are not commonly associated. All the elements listed occur in at least trace amounts in many fluorspar deposits, and barium, manganese, strontium, and yttrium are consistently present. Fluorspar deposits containing trace metals, or grading into associated metal deposits, are too numerous to list. It is commonly the earthy and porcelaneous varieties of fluorspar in breccia zones that contain anomalous amounts of metals. Anomalous amounts of molybdenum occur within and around a fluorspar vein in the Northgate district, Colorado. The source of the anomaly is a minor depositional phase of porcelaneous material composed of chalcedonic quartz, fluorite, pyrite, and scattered molybdenite. This same material pervasively entered and altered the wall rocks for distances up to 50 feet (Worl, in U.S. Geological Survey, 1970, p. A5). Gold veins in the Steeple Rock district, New Mexico, contain fluorite gangue, and genetically related fluorspar veins in the same district contain trace amounts of gold. Fluorspar deposits in the Vulture Mountains, Ariz.; Sierra Caballo, N. Mex,; and Yankee Fork district, Idaho, are related to lead-silver and gold deposits that occupy the same structures. For many more examples of fluorspar deposits containing concentrations of other elements, see Worl, Van Alstine, and Heyl (1973).

Igneous associations with this type of fluorite are difficult to define; many deposits such as those in the Northgate district, Colorado (Steven, 1960), are many miles from any known Tertiary igneous activity, and many deposits that do occur within volcanic rocks have not been proved to be genetically related to that rock or even to the volcanic event that was the source of the rock. In a few places, however, it seems that the fluorite is genetically related to the enclosing volcanic rock. In the Cady Mountains, Calif., fluorite stringers, veinlets, and pods occur through breccia zones in basalt and andesite flows. The basalt and andesite contain disseminated fluorite, mainly as a filling of vesicules (Dibblee and Bassett, 1966). The Moneymaker fluorspar deposit, Burro Mountains, N. Mex. (Williams, 1966, p. 49), is composed of

veins in a major fault zone. The veins are adjacent to and parallel to a rhyolite dike that contains pods, segregations, and disseminations of fluorite. The large fluorspar veins northeast of Winston, N. Mex., are within the same structure and parallel to a large fluorite-bearing rhyolite dike. Fluorite mineralization in southern New Mexico has been related to late Tertiary volcanism (Rothrock, 1970, p. 125), and the distribution of this type of fluorite (Figs. 2 and 3) is similar to the distribution of fluorine- and fluorite-rich volcanic rocks (D. R. Shawe, personal commun., 1973).

The age of fluorspar deposits of this type can be determined only relatively by crosscutting relationships; none of the deposits have been radiometrically dated. It does seem, however, that most formed roughly 5 to 20 million years ago, during the same general time span as some of the volcanism in parts of the West. Several minor occurrences of fluorite in hot-spring deposits are probably younger. Fluorite, manganese, gold, uranium, and silver mineralization in southwest New Mexico occurred in late Miocene or Pliocene as contrasted to earlier Tertiary base-metal sulfide mineralization (Gillerman, 1970, p. 118). Numerous fluorspar deposits in New Mexico and southeastern Arizona occur within the extensive Pliocene and Pleistocene Gila Conglomerate, and in the Redrock area, New Mexico, fluorspar veins extend into basalt flows (presumably Pliocene or Pleistocene) overlying the Gila Conglomerate. Many fluorspar deposits in this region are situated within basin and range faults that are younger than 20 m.y. (Elston, 1970, p. 150). Several deposits in southwestern Arizona cut the Pliocene Bouse Formation, and in the Trigo Mountains they apparently cut even younger volcanic flow rocks. The basalt and andesite in the Cady Mountains, Calif., that contain veins and disseminations of fluorite are Miocene or possibly younger (Dibblee and Bassett, 1966). Fluorspar veins at several locations in Nevada crosscut a sequence of volcanic rocks radiometrically dated as 16 to 10 m.y. old (for example, see McKee and Silberman, 1970). Fluorite-bearing gold deposits at Jarbridge, Nev., are considered to be late Miocene (Roberts and others, 1971, p. 29). The extensive fluorspar deposits in the Browns Canyon district, Colorado, were probably formed during the late Miocene (Van Alstine, 1969, p. 37).

Fluorite not associated with intrusive igneous rocks formed by deposition from relatively cool and generally dilute hydrothermal fluids, probably not greatly different from the waters issuing from many present thermal springs. It is commonly thought that the great bulk of the water was meteoric and probably slightly alkaline. Fluorine, and possibly some of the other constituents, probably had a deep source, either volatiles escaping from a crystallizing magma at depth or derived directly from a deep crust or upper mantle source. The concentration of fluorine in the waters at the time of deposition is unknown. Thermal waters now depositing very minor fluorite or associated with fluorspar deposits at Ojo Caliente, N. Mex., and Poncha Springs and Browns Canyon, Colo., contain 12 to 16 ppm fluorine (White, 1955, p. 143).

The paragenetic sequences of several districts indicate numerous depositional stages generally separated by brecciation. Most depositional stages were monomineralogic; the exceptions were those that deposited porcelaneous and earthy fluorspar (both a mixture of fluorite, chalcedonic quartz, and other minerals). Deposits at Hansonburg, N. Mex., formed from several stages of deposition, the first producing sphalerite, pyrite, galena, and chalcopyrite, and the last calcite. All the intermediate stages were primarily fluorite. Temperatures of deposition, as determined from homogenization temperatures of fluid inclusions, during the early fluorite stages were 205° to 180°C and decreased during the later stages to about 140°C. The salinity increased from 10 to 16 weight percent during fluorite deposition (Roedder, Heyl, and Creel, 1968). Fluorspar in the Browns Canyon district, Colorado, was deposited in many stages from slightly alkaline solutions at temperatures of 119° to 168°C, as determined by homogenization of fluid inclusions. The ore-forming solutions were very dilute and probably a mixture of meteoric water with minor amounts of hydrothermal waters (Van Alstine, 1969, p. 37). Fluorspar veins at Northgate, Colo., formed by deposition during several stages and substages often interrupted by periods of brecciation. Most stages of deposition were monomineralic, forming layers of columnar fluorite, but several stages, usually during and following periods of brecciation, produced fine-grained mixtures of fluorite, chalcedonic quartz,

pyrite, and lesser amounts of barite, manganese oxides, and molybdenite. The ore-forming solutions were very dilute fluids (salinities less than about 2 weight percent). Temperatures of the fluids at the time of deposition were 130° to 175°C as determined by homogenization temperatures of fluid inclusions (J. T. Nash, oral commun., 1970).

The direct connection between fluorspar deposits and extinct hot springs can be seen in several areas. Fluorite-manganese oxide veins in the Animas Mountains (Elston, 1965, p. 212) and the Redrock area, New Mexico, pass upward, within a few feet, into banded travertine at the surface. Fluorspar deposits along the west side of the Burro Mountains, N. Mex. (Gillerman, 1964, p. 72), consist of small veins extending a short distance away from a major fault zone. The fluorspar veins grade along strike into banded travertine and apron deposits of extinct hot springs. The Madrasco deposit, Nevada (Horton, 1961, p. 9), consists of fluorite pods and disseminations in rock of extinct hot springs aprons.

Fluorspar deposits not associated with intrusive igneous rocks are in many areas related to zones that have undergone tensional faulting. These zones trend mainly north to northwest or northeast, but in southwestern Arizona and southeastern California they trend east. The distribution of basin and range faulting in the West coincides closely with the distribution of this type of fluorite (Figs. 2 and 3). The alignments of fluorspar deposits closely parallel the structural zones; deposits occur both within the structural zone and nearby in subsidiary structures. Numerous deposits occur along faults of the Rio Grande rift system in New Mexico (Rothrock, 1970, p. 241, and Elston, 1970, p. 147) and its northern extension into Colorado. Faults of this system probably extend to the north and include the mineralized faults in the Northgate district, Colorado (Tweto, 1968, p. 582). Most of the deposits in the Silver City area, New Mexico, are aligned along major northwest-trending fault zones and along less distinct northeast-trending fault zones.

In some areas the alignment of deposits and the structure of the deposits reflect major structures that may be older than the north-trending range-bounding faults and the structural grain of the Basin and Range province. Fluorspar deposits in

the Lovelock area, Nevada (Horton, 1961, p. 21) are mainly within and aligned along major fault systems that trend N. 20°-40° W. These faults are transverse to the attitude of the enclosing mountain ranges and to the major north-trending structural grain of the region. Deposits in the Indian Peaks area, Utah, are aligned along a northwest-trending fault system that does not parallel the general north-trending structural grain of the region. In addition, the Indian Peaks deposits are just one of many districts that are aligned along a well-defined northeast-trending zone of mineralized, altered, and intrusive centers. (See Worl, Van Alstine, and Heyl, 1973.)

CONCLUSIONS

A large part of the Western United States is underlain by crustal rocks relatively enriched in fluorine. The fluorine concentrations within the rocks are of several types. The most abundant and most promising for future exploitation are Tertiary late-magmatic and hydrothermal deposits of two general types: those associated with intrusive igneous rocks, and those not associated with intrusive rocks. The similarities and differences of the two types are summarized in Table 1. Exploration for these deposits should be primarily within the fluorine-rich areas and should be oriented toward the important geologic parameters as outlined in Table 1. Exploration for deposits associated with intrusive rocks should be directed toward intrusive centers characterized by late-magmatic activity of an alkalic nature that exhibited an abundance of volatiles during that stage. Silicified rock, fluorite, and secondary sericite, biotite, or potassium feldspar within or near an intrusive are favorable indicators, as are stockworks of these same minerals. The most favorable hosts are carbonate sedimentary and silicic igneous and metamorphic rocks. The silicic rocks make an excellent host for large mineralized breccia zones, and the carbonates are excellent hosts for large massive replacement bodies as well as mineralized breccias.

Important factors to be considered in searching for deposits not associated with intrusive rocks are large Tertiary fault systems that are generally tensional in nature. Most favorable hosts are again brecciated calcareous sedimentary and silicic igneous and metamorphic rocks. Areas of fluorine-rich volcanic rocks, massive silicified rock, and recent and extinct hot-springs activity are also good exploration guides.

Other types of fluorine concentrations that deserve consideration are complex pegmatites, carbonatite complexes, and lacustrine and volcaniclastic sedimentary rocks. Complex pegmatites exploited in Montana, the Crystal, Spar, and Snowbird properties, are not well studied in terms of age, mode of emplacement, origin, geochemistry, and structural control. Similar unrecognized deposits may exist in other parts of the West. Carbonatite complexes exist in the West but none have been a commercial source of fluorine. Lacustrine deposits similar to those near Rome, Oreg. (Sheppard and Gude, 1969), deserve serious consideration as future fluorine resources. Beds that coincide in time and space with hydrothermal fluorite and fluorine-rich volcanism may contain fluorite concentrations.

Several factors will have to be overcome before the production of fluorspar increases substantially in the Western United States. Transportation is a problem in many areas as there is a lack of large local consumers and the distance to the present large consumers may be great. Many known deposits are many miles from the nearest community or railhead. Foreign competition, especially from large deposits being exploited in Africa and South America, will become increasingly strong. These stable sources will probably be able to supply fluorspar to the major United States consumers in the near future more cheaply than can the fluorspar deposits currently being exploited in the Western United States. However, the incentive for increasing fluorspar production in the West is present. The United States is currently producing only 20 percent of the approximately 1,600,000 tons of CaF_2 consumed annually. Large areas of the West contain relatively fluorine-rich crustal rocks, and the possibilities are excellent for developing large low-grade deposits with coproducts or byproducts.

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SOME FLUORITE-BARITE DEPOSITS IN THE MISSISSIPPI VALLEY IN RELATION TO MAJOR STRUCTURES AND ZONATION[1]

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Many of the fluorite-barite deposits in the eastern parts of the Mississippi Valley lie along major basement lineaments or at the intersections of lineaments. An east-trending lineament that extends approximately along the 38th parallel of latitude from western Virginia into south-central Missouri (Heyl, 1972) is the most important commercially. The Illinois-Kentucky and the Central Kentucky districts lie along this lineament at its intersection with other major structures.

The Illinois-Kentucky district (Grogan and Bradbury, 1968) is centered around greater Hicks dome, just south of the intersection of the 38th parallel lineament and the New Madrid fault zone (Fig. 1). The galenas of the district contain more silver and antimony near Hicks dome, but became progressively leaner in these elements peripherally, especially toward Princeton, Kentucky. The zonal pattern suggests areas favorable for discovery of new deposits beneath the overlying Pennsylvanian strata northward, northeastward, and northwestward from the center of the dome.

The Central Kentucky district (Fig. 2) lies on the crest of the Lexington dome at the intersection of the 38th parallel lineament and the Cincinnati arch. The vein district is zoned with fluorite, which is more abundant centrally, and with strontian-barite, and galena, which are more abundant peripherally (Jolly and Heyl, 1964). Similar mineral deposits extend southward at intervals along the Cincinnati arch and in fault zones which occur at intervals along its crest into Tennessee (Taylor, 1962).

The Central Tennessee district is on the crest of the Nashville dome. Here, fluorite, strontian-barite, and sphalerite occur with the same mineral habits and trace elements as in central Kentucky. Large breccia pods and blankets of fluorite and barite and some sphalerite, as well as sphalerite alone, occur in the Knox Dolomite. Small veins similar to those in central Tennessee are above in the Middle Ordovician limestones (Jewell, 1947).

New fluorspar deposits should be looked for in major domes and arches east of the Mississippi River, and along major lineaments. Promising areas include: (1) the southern part of the Nashville dome, (2) the crest of the Cincinnati arch in southern Kentucky, (3) the crest of the Findlay arch south of Toledo, (4) the Ste. Genevieve fault zone in Illinois and Missouri, (5) the Mt. Carmel fault zone in southern Indiana, and (6) the Frontenac arch in southern Ontario and western New York.

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91° 90° 89° 88° 87° 86°

MISSOURI

MISSOURI RIVER

CAG

St Louis

ILLINOIS

BASIN

MT CARMEL FAULT

Louisville

38°

BIG RIVER FAULT

PALMER FAULT

CROOKED CREEK

OZARK

BLACK FAULT

DOME

ST FRANCOIS MOUNTAINS

FARMINGTON ANTICLINE

STE GENEVIEVE RIVER

COTTAGE GROVE FAULT

MISSISSIPPI RIVER

NEW MADRID FAULT ZONE

Evansville

OHIO RIVER

MULDRAUGH DOME

INDIANA
KENTUCKY

Shawneetown

HICKS DOME

ROUGH CREEK FAULT ZONE

WESTERN KENTUCKY COAL BASIN

3

37°

FAULT ZONE

Paducah

KENTUCKY
TENNESSEE

MISSOURI
ARKANSAS

New Madrid

NEW MADRID FAULT ZONE

INDIAN MOUND
CAVE SPRING
WELLS CREEK

0 25 50 100 MILES

EXPLANATION

Tertiary and Cretaceous rocks

X Permian, Devonian and Cambrian intrusions of peridotite

Precambrian rocks

Anticlinal axis

Occurrences of galena, sphalerite, barite, fluorite

Permian and Pennsylvanian rocks

Pre-Pennsylvanian rocks of Paleozoic age

U
D
Fault
Showing relative movement

Monoclinal axis

Synclinal axis

Cryptoexplosion structure

5 Large mineral district

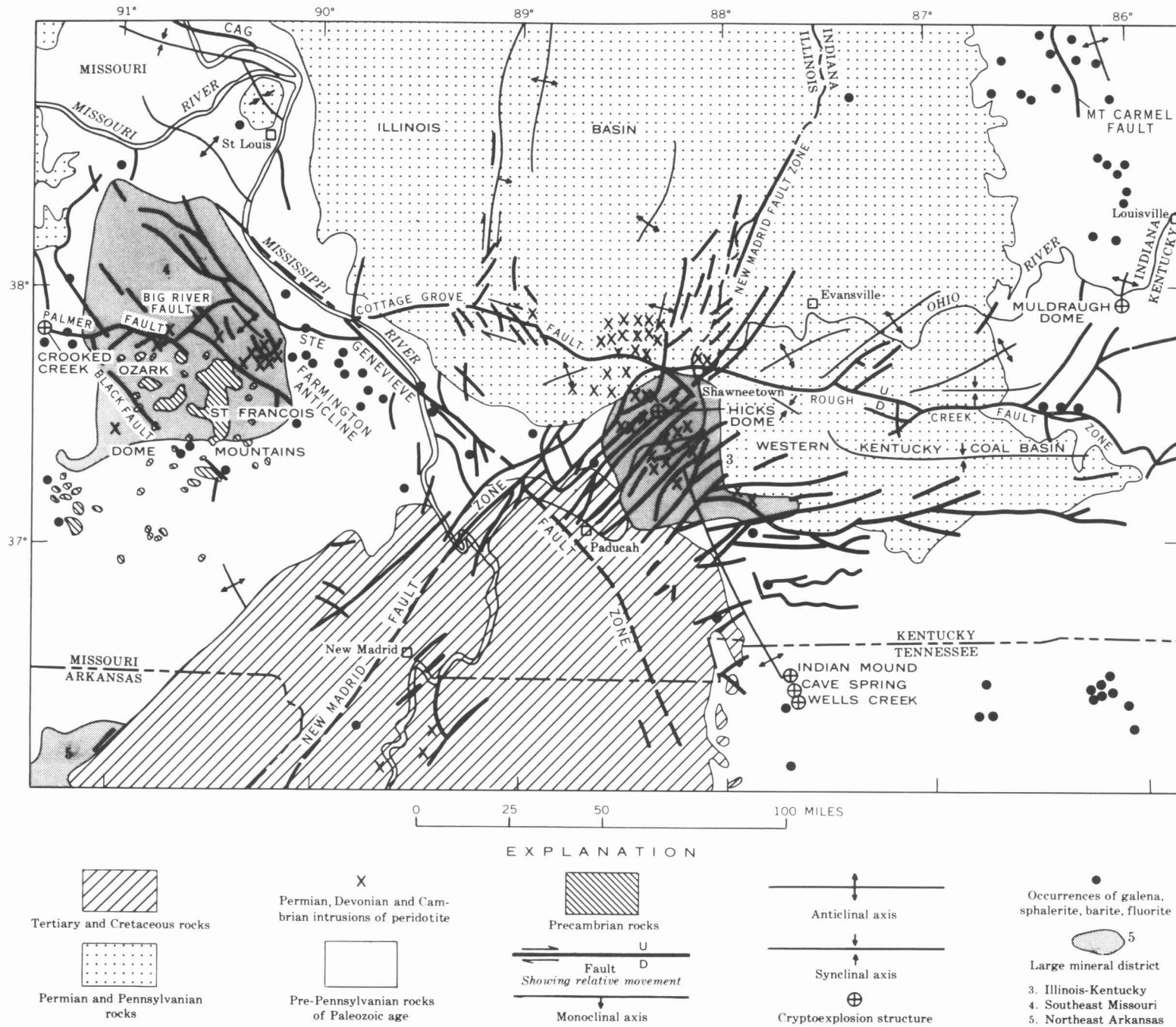3. Illinois-Kentucky
4. Southeast Missouri
5. Northeast Arkansas

Figure 1. Major structures of the Illinois-Kentucky district and surrounding region. (Reproduced from *Economic Geology*, 1972, vol. 67, p. 886.)
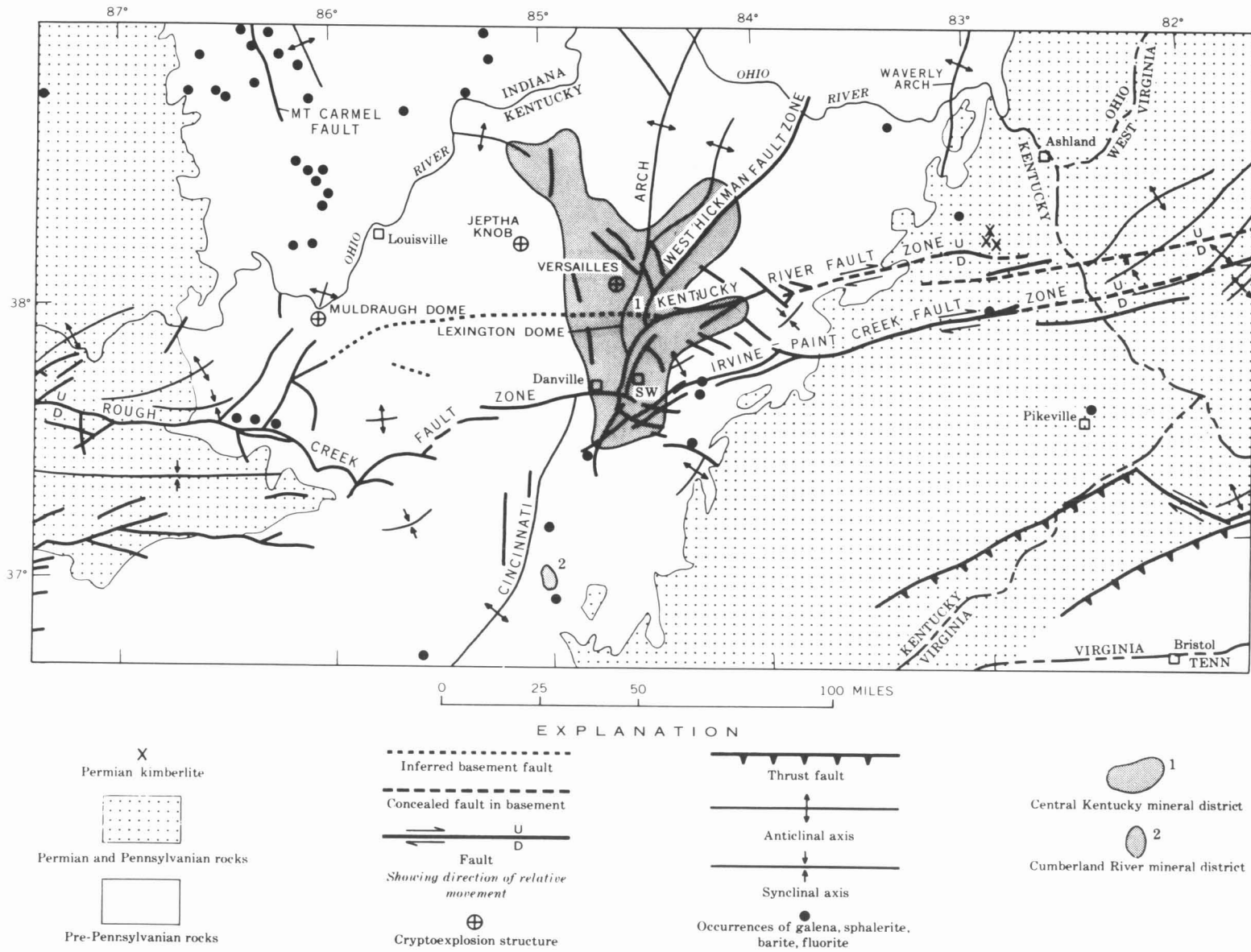
Figure 2. The Central Kentucky district and major structures which control the district. (Reproduced from *Economic Geology*, 1972, vol. 67, p. 883.)

ILLINOIS-KENTUCKY FLUORSPAR DISTRICT[1]

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ABSTRACT

The Illinois-Kentucky fluorspar district is the largest producer of fluorspar in the United States. The deposits occur in sedimentary rocks of Middle and Late Mississippian and Early Pennsylvanian age. Some mafic dikes and sills and dike- or plug-like bodies of breccia intrude the sedimentary rocks.

The fluorspar is localized either as veins along a series of complex northeast-trending, steeply dipping normal fault zones or as bedding-replacement deposits principally along three horizons in rocks of Mississippian age. A structural high, centered at Hicks dome in Illinois, crosses the area in a northwesterly direction.

The deposits are composed principally of calcite and fluorite, with subordinate quantities of sphalerite, galena, and barite. Abnormally high quantities of thorium, beryllium, and rare earths are present in the breccias near Hicks dome.

Most geologists consider that the deposits are epigenetic and that the ore elements mostly were carried upward by hot connate water as a result of deep-seated igneous activity. A syngenetic origin for the deposits also has been proposed.

As a result of several discoveries within the last several years, and the still substantial amount of inadequately tested or untested ground, potential production of fluorspar from the area is considered good.

LOCATION, HISTORY, AND PRODUCTION

More than three-fourths of the fluorspar produced in the United States has come from the Illinois-Kentucky district. Substantial quantities of zinc and some lead and barite also have been produced, usually as a byproduct of fluorspar mining.

The Illinois-Kentucky fluorspar district is in Hardin and Pope Counties in southeasternmost Illinois and in adjacent Crittenden, Livingston, and Caldwell Counties of western Kentucky (Fig. 1). Nearly all the mines or mineralized areas are within the boundaries of 17 7.5-minute quadrangle maps that comprise an area of about 1,000 square miles (Fig. 2). The Illinois State Geological Survey has published geologic maps of the

Illinois part of the district, and the U. S. Geological Survey, in cooperation with the Kentucky Geological Survey, has published several geologic maps and has completed the field work for geologic maps of the remaining five quadrangles in the Kentucky part of the district (Fig. 3).

The earliest mining in the district was for lead and was done at the Columbia mine, Crittenden County, Ky., in 1835 (Ulrich and Smith, 1905, p. 115). Lead mining started in 1842 in Illinois (Bastin, 1931, p. 10; Norwood, 1866). From 1835 to the early 1870's little fluorspar was mined. Only small amounts were produced from the early 1870's to about 1890, when an expanded market was created by the development of the basic open-hearth steel furnace in which fluorspar was used for flux. Production since 1890 has been erratic but in general has risen. Production during World Wars I and II and the Korean conflict rose sharply, but because of rising imports during
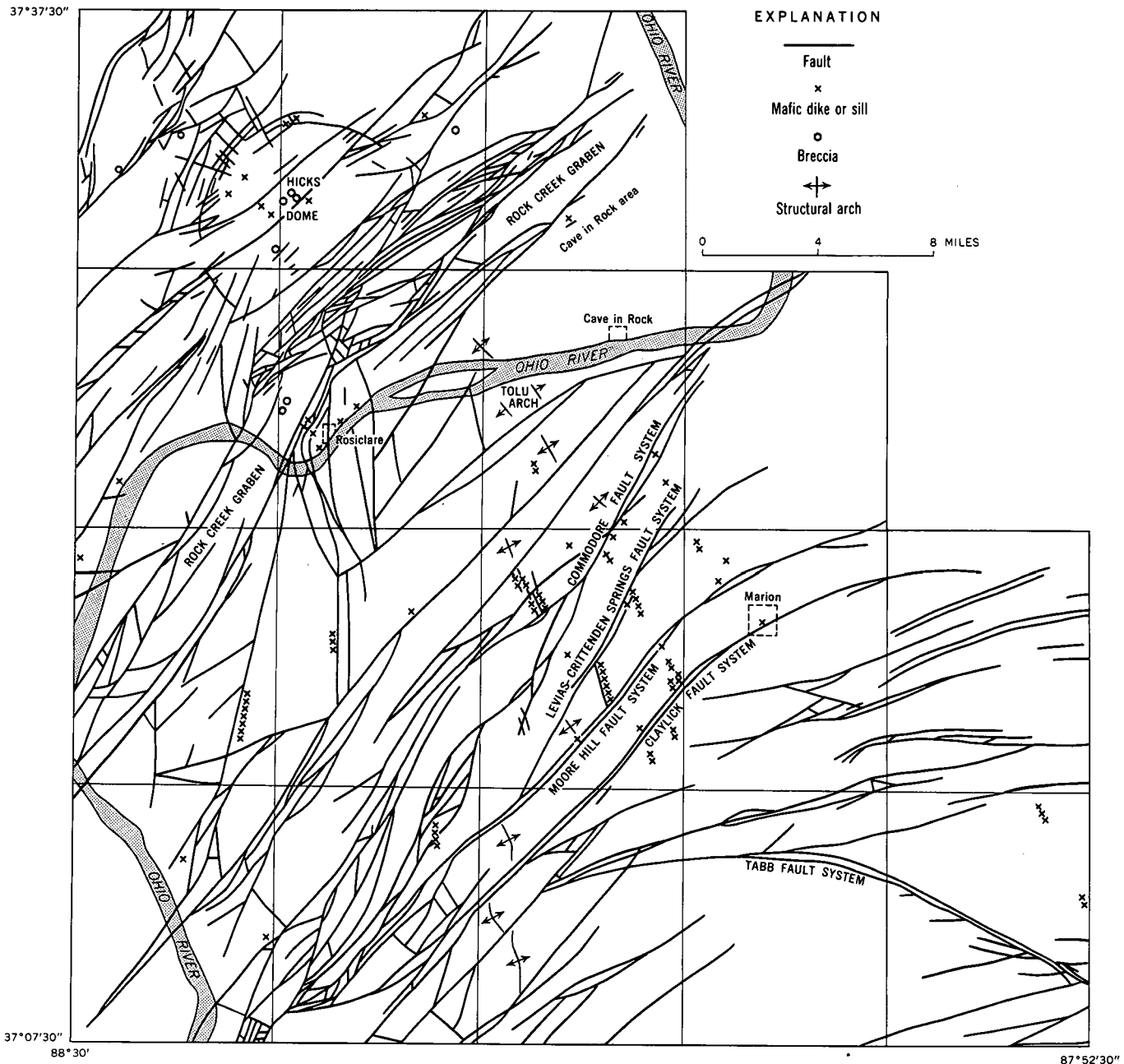

Figure 1. Major structural features of the Illinois-Kentucky fluorspar district (compiled from 17 published and unpublished geologic maps of 7.5-minute quadrangles, 1962-1972, by the Illinois State Geological Survey and U. S. Geological Survey).

1953-58, production in the district decreased. Production rose in 1970 over 1969 and will probably increase further in the near future. Available fluorspar production figures are summarized in Table 1.

Zinc has been produced for many years, and since 1940 the district has become a major source of zinc, some as a byproduct, some as a main product. Substantial quantities of barite have been produced at intervals. Lead has been a minor byproduct in recent years, as have silver, cadmium, and germanium.

Until the early 1930's, almost the entire production from the district was from vein ores. Since then, the amount of ore produced from bedding-replacement deposits near Cave in Rock, Ill., has risen so that by the middle to late 1960's, this type of ore constituted more of the Illinois

Figure 2. Illinois-Kentucky fluorspar district, showing mineralized areas.

production than vein ore. The rise in the ratio of bedding-replacement ore to vein ore was in part due to the depletion of some of the large vein deposits near Rosiclare. Within the last few years, however, the Illinois production from veins has increased and may soon equal the production from bedding-replacement deposits. In Kentucky, practically all production has been from veins, although a substantial deposit of bedding-replace-

ment ore near Joy has been known since the 1950's and was put into production in 1970.

GEOLOGIC SETTING

Stratigraphy

Most of the sedimentary rocks that crop out in the district range in age from Late Devonian through Early Pennsylvanian, although in the

TABLE 1.—FLUORSPAR SHIPMENTS FROM ILLINOIS
AND KENTUCKY (FROM U. S. BUR. MINES MINERALS
YEARBOOK).

Illinois	Tons
Through 1963	6,163,345
1964	127,454
1965	159,140
1966	176,175
1967	210,207
1968	188,325
1969	88,480
1970	148,208
1971	141,000°
Total	7,402,334

Kentucky	
Through 1963	3,016,980
1964	38,214
1965	31,992
1966	28,725
1967	32,952
1968	17,050
1969	10,000†
1970	5,000†
1971	(Expected to increase)
Total	3,180,913

° Bur. of Mines estimate
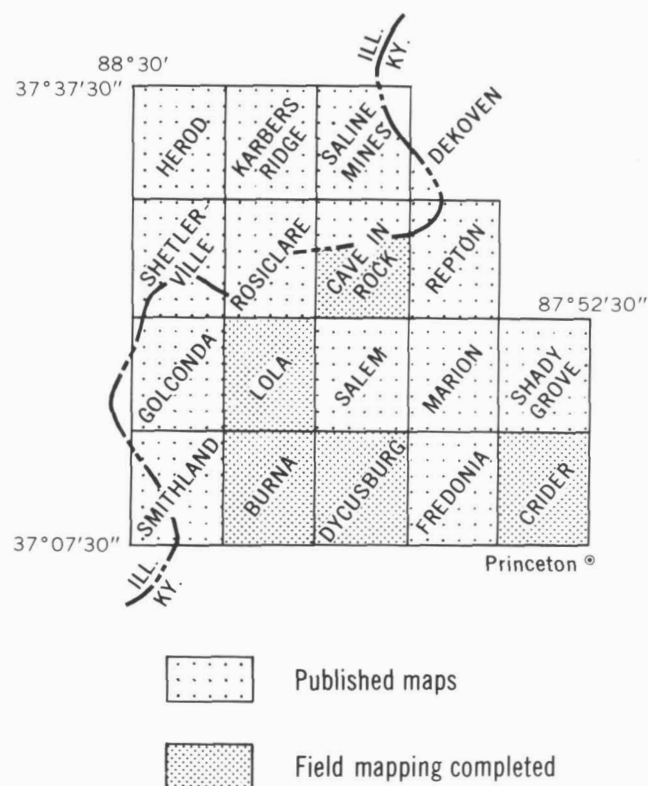† Writer's estimate

Figure 3. Status of geologic mapping of 7.5-minute quadrangles in the Illinois-Kentucky fluorspar district.

more productive areas, the rock units at the surface are the Meramecian and Chesterian Series of Late Mississippian age. Lower Pennsylvanian rocks are present also in several places, and small amounts of unconsolidated sand, silt, clay, and gravel of Cretaceous and Tertiary age and loess and alluvium of Quaternary age are present locally.

The stratigraphic column of exposed formations in the district, as summarized by Grogan and Bradbury (1968, Fig. 2), is given in Figure 4. The stratigraphic column for the Kentucky part of the district is shown in Figure 5. The lithology in Illinois and Kentucky is generally similar, but stratigraphic nomenclature differs.

Most of the vein and bedding-replacement ores occur where the wall rocks are of either early Chesterian or late Meramecian age. (See Figs. 4 and 5.)

Dikes, Sills, and Breccias

Many mafic dikes and, less commonly, sills are present in the district; in Illinois, dike- or plug-like bodies of breccia (Fig. 1) occur in rocks of Paleozoic age.

The mafic dikes and sills have been called mica peridotites and lamprophyres (Koenig, 1965). Most are so highly altered that they defy precise classification; available analyses indicate they are mafic alkalic rocks. The dikes and sills are mostly dark gray to dark greenish gray, finely crystalline, and commonly slightly porphyritic. They are composed primarily of carbonates—both dolomite and calcite—serpentine, chlorite, and biotite (generally phlogopitic). Small quantities of magnetite, leucoxene, marcasite, fluorapatite, garnet, perovskite, and goethite are commonly present. Olivine and pyroxene occur as primary constituents, but in most of the dikes, these minerals have been largely altered to serpentine (Clegg and Bradbury, 1956; Koenig, 1956; Trace, 1962a).

Rarely, the mafic rock is medium to coarsely crystalline (sample no. 197 in Zartman and others, 1967) or is light gray and free of chlorite or serpentine. Oesterling (1952, p. 324) described light-green dike material composed ". . . nearly entirely of fine-grained calcite. The phlogopite has been completely replaced by calcite; there is no indication that olivine or pyroxene phenocrysts were ever present. . . ."

SYSTEM	SERIES	FORMATION	MEMBER	LITH-OLOGY	THICK-NESS (FT.)	LITHOLOGIC DESCRIPTION	RANGE OF DEPOSITS VEINS	RANGE OF DEPOSITS BEDDED
PENNSYLVANIAN					600-900	Sandstone, shale, thin coals		
MISSISSIPPIAN	CHESTERIAN	KINKAID			0-80	Gray, cherty limestone; shale		
		DEGONIA			0-30	Shale and thin-bedded sandstone		
		CLORE			100-120	Shale; limestone; thin-bedded sandstone		
		PALESTINE			50-60	Sandstone; silty shale		
		MENARD			100-130	Fine-grained limestone; shale		
		WALTERSBURG			15-50	Shale; shaly sandstone		
		VIENNA			10-20	Limestone; shaly limestone		
		TAR SPRINGS			90-110	Sandstone; shale; thin coal		
		GLEN DEAN			40-70	Fossiliferous, partly oolitic limestone; shale		
		HARDINSBURG			90-115	Sandstone; shale		
		HANEY				Fossiliferous limestone		
		FRAILEYS			105-140	Shale; thin limestone		
		BEECH CREEK				Silty limestone		
		CYPRESS			80-110	Sandstone; shale		
		RIDENHOWER			25-65	Shale; shaly sandstone		
		BETHEL			80-100	Sandstone		
		DOWNEYS BLUFF			25-40	Crinoidal, locally oolitic limestone		
		YANKEETOWN			30-45	Shale; siltstone (Yankeetown); limestone; shale (Shetlerville)		
		RENAULT	Shetlerville / Levias		15-35	Light-colored oolitic limestone (Levias)		
		AUX VASES	Rosiclare		15-35	Calcareous sandstone, shale at base		
		STE.GENEVIEVE	Spar Mtn.		120-160	Light-colored, largely oolitic limestone; sandstone lenses		
	VALMEYERAN	ST. LOUIS			350-400	Fine-grained, cherty limestone		
		SALEM			500±	Dark-colored, fine-grained limestone; foraminiferal calcarenite		
		ULLIN			125-360	Crinoidal, bryozoan limestone; dark-gray, fine-grained limestone		
		FORT PAYNE			225-640	Siltstone; silty, cherty limestone		
		SPRINGVILLE				Gray and greenish gray shale		
DEVONIAN-MISSISSIPPIAN		NEW ALBANY GROUP			395±	Gray to black shale		
DEVONIAN		LINGLE						
		GRAND TOWER			250±	Limestone and chert		
		CLEAR CREEK						

Figure 4. Stratigraphic column of exposed formations in the Illinois-Kentucky mining district. Range of deposits columns are scaled to correlate with lithology column, e.g., the three main bedded horizons are the top part of the Downeys Bluff, top part of the Ste. Genevieve, and the Spar Mountain Member. (*From* Grogan and Bradbury, 1968, fig. 2, p. 375, *as adapted from* Baxter and others, 1967, pl. 1. Reprinted courtesy AIME.)

Chemical and semiquantitative spectrographic analyses of samples from the Illinois dikes and sills were reported by Bradbury (1962) and chemical analyses of similar samples from Kentucky by Koenig (1956). Semiquantitative spectrographic analyses of a sample from the highly weathered Robinson dike on Hicks dome, described by Bradbury and others (1955, p. 8), and a sample from a similarly altered dike in the east-central part of the Salem quadrangle, Kentucky (Trace, 1962a), showed that the Robinson dike contained much larger quantities of rare earths than did the Kentucky dike (see Table 2).

The number of identified dikes and sills has increased considerably in the district in the last two decades, principally because of an increase

SYSTEM	SERIES	FORMATION AND MEMBER	LITHOLOGY	THICKNESS, IN FEET	DESCRIPTION
PENNSYLVANIAN				60-765	Sandstone, shale, thin coals
MISSISSIPPIAN	Chesterian	Kinkaid Limestone		0-165	Limestone, sandstone, and shale
		Degonia Sandstone		5-38	Shale and sandstone
		Clore Limestone		70-125	Shale and limestone; thin sandstone
		Palestine Sandstone		30-75	Sandstone and shale
		Menard Limestone		80-145	Limestone and shale; thin sandstone locally
		Waltersburg Sandstone		20-60	Shale, siltstone, and sandstone
		Vienna Limestone		15-35	Limestone, cherty
		Tar Springs Sandstone		70-120	Sandstone and shale; thin coal locally
		Glen Dean Limestone		40-95	Limestone and shale
		Hardinsburg Sandstone		80-150	Sandstone and shale
		Golconda Formation		90-165	Shale and limestone; thin sandstone common
		Cypress Sandstone		45-140	Sandstone and shale; thin coal locally
		Paint Creek Formation		5-100	Shale, limestone, and sandstone
		Bethel Sandstone		20-120	Sandstone
		Renault Limestone		70-125	Limestone and shale
	Meramecian	Ste. Genevieve Limestone		200-300	Limestone, oolitic; thin sandstone
		St. Louis Limestone — Upper member		250± / 500-530	Limestone, cherty, partly oolitic
		St. Louis Limestone — Lower member		250-280	Limestone, cherty; containing *Lithostrotion* colonies
		Salem Limestone		120±	Limestone, oolitic at top
		Warsaw Limestone		230±	Limestone, large *Echinocrinus* spines at top
	Osagean	Fort Payne Formation		600±	Limestone, mostly dark gray and very cherty or silty; locally, upper part is light gray
DEVONIAN		Chattanooga Shale			Dark-gray shale

Figure 5. Generalized stratigraphic column of exposed formations in the Western Kentucky fluorspar district.

TABLE 2.—SEMIQUANTITATIVE SPECTROGRAPHIC
ANALYSES OF WEATHERED MAFIC DIKES, ILLINOIS
AND KENTUCKY.

Precent[*]	Robinson dike (near Hicks dome, Illinois)	Fowler dike (east-central part of Salem quadrangle, Kentucky
More than 10	Si	Si
5-10	Fe, Al	Fe, Al
1-5	Ti, Mg	Mg, Ca
0.5-1	Ca, K, Na	Ti, K
0.1-0.5	Ni, Y, Ba, Ce	Ni, Cr
0.05-0.1	Mn, Nd	–
0.01-0.05	La, Sr, V, Co, Cr, Zr, Cu	Mn, Ba, Na, Sr, V, Cu
0.005-0.01	Nb, Zn, Ga	Co, Ga
0.001-0.005	Yb, Pb, Mo, Sc, Be	La, Nb, Y, Pb, Nd, Zr, Mo, Sc
0.0005-0.001	–	–
0.0001-0.0005	Ag	Yb, Ag, Be

[*] Analyses by Mona Frank, U. S. Geol. Survey, Sept. 1955.

in diamond-drill exploration. Some in Illinois have been found during mining. A few have been found during areal mapping in Kentucky (Amos, 1966; Trace, 1966) and in Illinois. Probably many more have not been found because mafic rock on exposure decomposes within a few years and is difficult to recognize. Where continuously washed clean, as it is by Claylick Creek near the eastern edge of the Salem quadrangle (Trace, 1962a), mafic dike rock superfically resembles a dark-gray limestone.

Many breccias and breccia "dikes" have been mapped in the Illinois part of the district by Baxter and Desborough (1965) and by Baxter and others (1967), and have been described in some detail (Clegg and Bradbury, 1956; Brown and others, 1954). According to Baxter and Desborough (1965, p. 28), "The breccias consist of angular to subrounded fragments of sedimentary, metamorphosed sedimentary, and igneous rocks in a matrix of finely ground rock and mineral fragments. The mineral fragments include quartz, pyroxene, augite, hornblende, apatite, mica, and feldspar." Grogan and Bradbury (1968, p. 376) described fine-grained nepheline-feldspar rock in one of the breccias.

Many of these bodies of breccias, which are roughly circular or elliptical in plan and as much as 1,000 feet in diameter, are pipes or small stocks. Some of the breccia masses are vertical or steeply dipping linear bodies which resemble dikes.

Many of the breccias contain a variety of minerals, both on the surface and to depths of more than 2,000 feet (Brown and others, 1954, p. 897-900; Heyl and others, 1965, p. B11; Bradbury, 1962, p. 6-8; Trace, 1960). Minerals occurring in the breccia include fluorite associated with rare-earth elements, sphalerite, galena, barite, monazite, florencite, calcite, quartz, pyrite, brookite, biotite, rutile, xenotime, pyroxene, hornblende, feldspar, and apatite; the breccias also contain above-normal concentrations of beryllium, thorium, niobium, and zirconium.

Before the early 1960's, the dikes, sills, and breccias were dated as post-Middle Pennsylvanian on the basis of stratigraphic relations. Zartman and others (1967, p. 860-861) studied samples of biotite, phlogopite, and hornblende from the dikes, sills, and breccias; on the basis of radioisotope studies they reported that: "All the ages lie within experimental uncertainty of each other and given an average Early Permain age of 267 million years."

Alteration

Silicification is the most striking change in the wall rocks of veins along faults. Where at least one fault wall is a Chester sandstone, the sandstone close to or within the fault zone is altered to quartzite. Indeed, the tracing of "quartz reefs" or fragments of quartzite is the best means of mapping faults in some areas. Study of a few thin sections of quartzite from the Commodore area in the Salem quadrangle suggests that little or no secondary silica has been added to the sandstone. Pore space in the quartzite is essentially non-existent, and the rock consists of tightly grouped and embayed angular to subrounded quartz sand grains. Hardin (1955, p. 24) suggested that in the Babb area in the Salem quadrangle the "secondary silicification appears to have been of more significance than pressure in the conversion of sandstone to quartzite."

The alteration of limestone wall rocks generally is slight to moderate. In places, many small doubly terminated quartz crystals and small masses of chalcedony have been reported (Hardin, 1955, p. 24; Trace, 1962b, p. 17; Trace, 1954, p. 70) where limestone is adjacent to a vein. Fragments of dolomitic limestone, which is a relatively common country rock of the area, are present within the veins. No secondary dolomitization of the wall rocks of vein deposits has been reported, but very

little research has been completed on this possibility to date.

Hall and Heyl (1968, p. 661) described visibly altered wall rocks as much as 100 feet laterally from a bedding-replacement deposit. According to them, geochemical and clay-mineral studies have shown that alteration includes solution thinning, silicification, dolomitization, and clay-mineral alteration. Brecke (1962, p. 525-530) described the alteration of country rock, primarily within the mineralized zones, as decalcification, dolomitization, and silicification. According to Pinckney and Rye (1972, p. 4), limestone wall-rock alteration in the Hill mine near Cave in Rock, Ill., included dolomitization, recrystallization of limestone, and silicification of both limestone and dolomite.

Structure

According to Heyl and Brock (1961, p. D3), "The Illinois-Kentucky mining district is centered in the most complexly faulted area in the central craton of the United States. Structural studies suggest that the mining district lies within a collapsed, block-faulted, sliced, and partly rotated domal anticline that is located at and near the intersections of several major fault lineaments." (See Fig. 6.) Heyl (1972) has related the fluorspar district to the intersection of the 38th parallel lineament with the New Madrid fault system.

Within the fluorspar district (see Fig. 1) the rocks are complexly broken by a series of steeply dipping to vertical normal or gravity faults that trend dominantly northeast and break the area into elongated northeast-trending blocks. Many
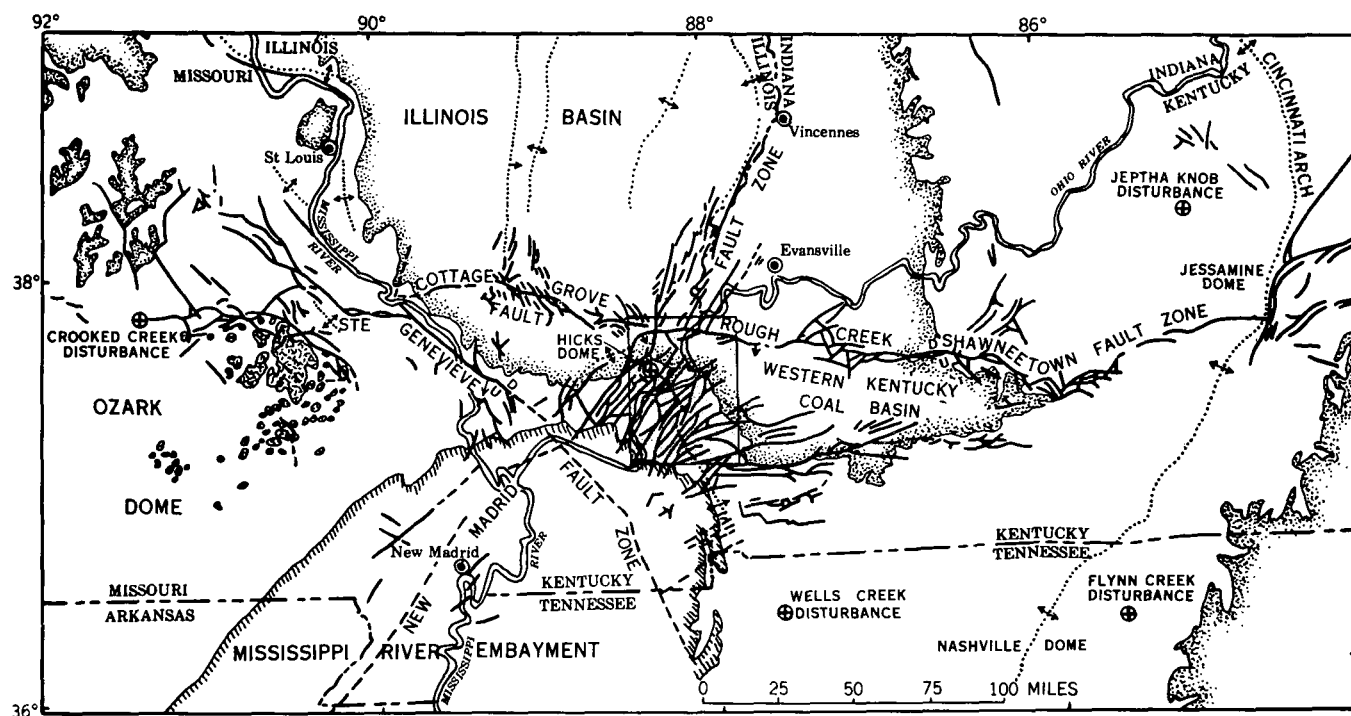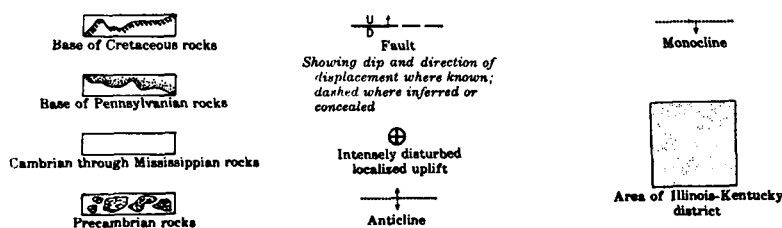

EXPLANATION

Figure 6. Major structural features near the Illinois-Kentucky mining district. Geology compiled from many published sources by A. V. Heyl, Jr., J. L. Jolly, C. E. Wells, and M. R. Brock. (*From* Heyl and Brock, 1961, fig. 294.1.)

cross faults that trend north to northwest are occupied in places by mafic dikes. Near the east edge of the Kentucky part of the district, the faults trend more to the east; in Illinois, radial and arcuate faults surround Hicks dome.

Hicks dome is a structural high with about 4,000 feet of vertical uplift that is centered in the southwest part of the Karbers Ridge quadrangle, Illinois (Baxter and Desborough, 1965). Brown and others (1954) described the dome as an incipient cryptovolcanic structure on the basis of breccias in an oil-test hole, nearby exposed arcuate faults, and the unusual quantities of rare earths, thorium, and beryllium in these breccias. As a result of an aeromagnetic survey, McGinnis and Bradbury (1964, p. 11) stated that Hicks dome is not underlain by a laccolithic intrusion, but they observed that: "A broad magnetic anomaly of relatively low intensity centered about $5\frac{1}{2}$ miles northeast of Hicks dome and the featureless configuration of contour lines around the anomaly suggest a large igneous body overlain by a thick sedimentary rock section."

The southeasterly extension of the dome is partly obscured by a 4- to 5-mile-wide fault zone, largely a downdropped area known as the Rock Creek graben. Southeast of the graben, the structural high reappears as the Tolu dome or arch, which is centered about a mile east of Tolu, Ky., in the Cave in Rock quadrangle (Baxter and others, 1963; Trace, unpub. data).

Southeast of the Tolu arch is another series of grabens (Weller and Sutton, 1951), bounded on the south by the Tabb fault system (Rogers and Hays, 1967). Because of the many faults within this part of the district, the structural high is more difficult to trace; a possible extension is shown on the Salem quadrangle (Trace, 1962a) between the Levias-Crittenden Springs and the Moore Hill fault systems. Further south, in the Dycusburg quadrangle, mapping (see Fig. 1) suggests three more possible segments of the arch (D. H. Amos, written commun., 1972).

Nearly all faults in the district are called normal and dip generally 75° to vertically; rarely are they inclined as low as 45°. Locally, the direction of dip of a fault or vein may be reversed, as shown in Figure 7. Along the edges of many of the larger grabens, fault zones consist of several
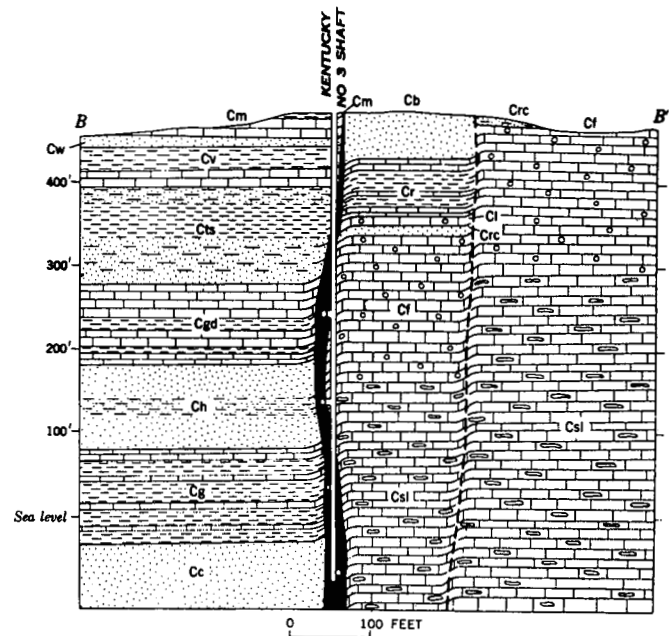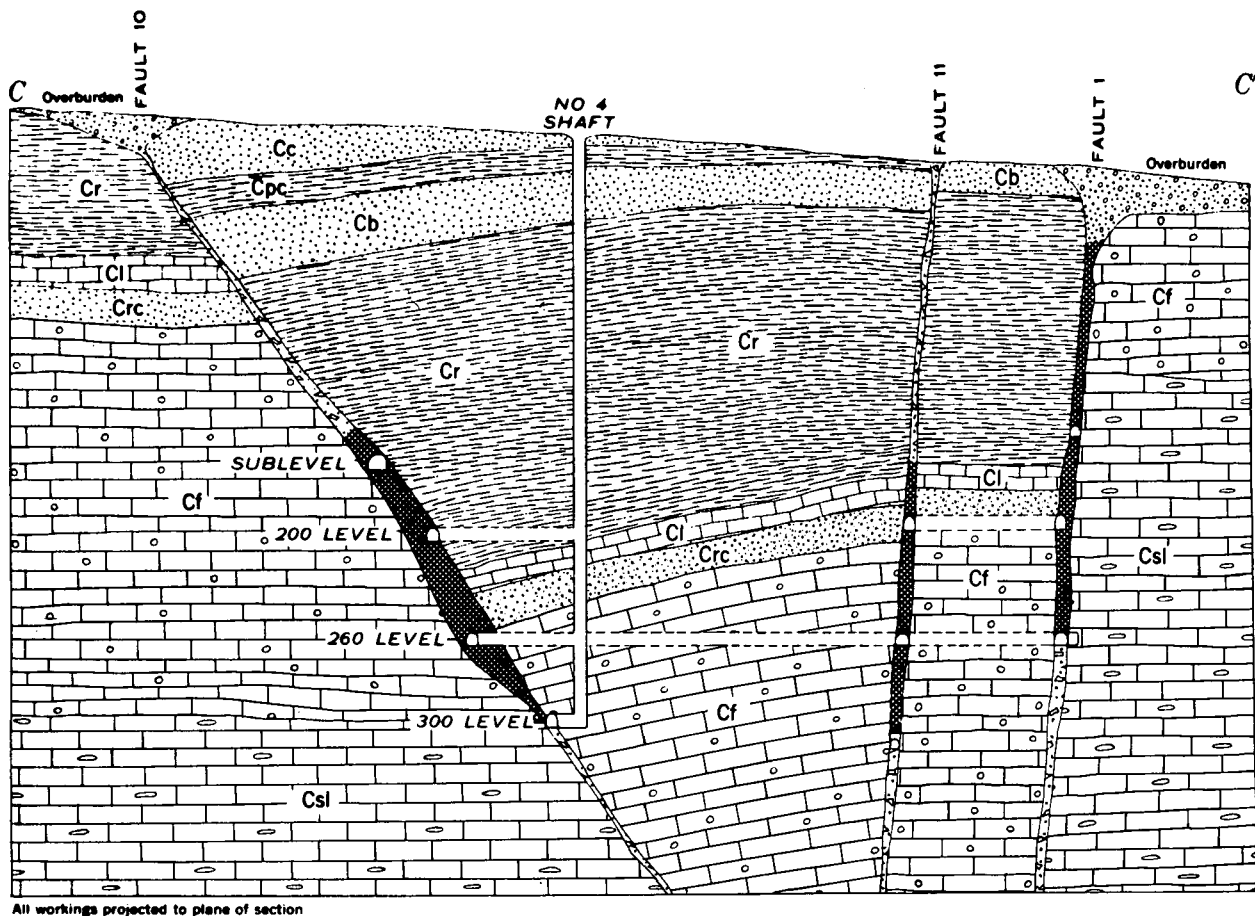

Figure 7. Cross section of Babb area, Crittenden County, Ky., showing dip of vein. (*From* Hardin, 1955, part of pl. 4.)

subparallel and sinuously intersecting fractures. These zones are commonly a few hundred feet wide, although at places they are more than 1,000 feet wide. The total displacement attributable to a fault zone is commonly distributed irregularly among the several individual faults—as step faults and also as small grabens within the fault zone. In places, the bounding faults of the zone may dip toward each other (Fig. 8). Minor faults may occur outside of, but within a few hundred feet of, the major fault zones—most commonly on the hanging-wall side.

Data regarding a dominant direction of movement along the northeast-trending faults are conflicting, perhaps suggesting that both vertical and some horizontal movement may have taken place. Vertical displacement generally is considered to have been the dominant direction of movement along the major northeast-trending faults in the district; some evidence of an unknown amount of horizontal movement, however, has been noted (Weller and Sutton, 1951). Clark and Royds (1948) and Heyl and Brock (1961) suggested that a horizontal component of movement may be significant.

Field mapping has shown that perhaps as much as 3,000 feet of vertical displacement has taken

EXPLANATION

Fault breccia

Fluorspar

Figure 8. Cross section of Davenport area, Crittenden County, Ky. (*From* Thurston and Hardin, 1954, part of pl. 14.)

place. Positive evidence for substantial horizontal movement is not obvious. For example, a dike swarm extending from the Glendale Church area southeast through the Columbia mine area to the Claylick Creek area in the Salem quadrangle of Kentucky (Trace, 1962a) is reasonably continuous even though it is crossed by two major fault zones. The relations suggest at best only a little post-dike horizontal movement. On the other hand, preliminary mapping of the Hicks-Tolu structural high southward through the Cave in Rock quadrangle (Trace, unpub. data) and the Dycusburg quadrangle (D. H. Amos, unpub. data) suggests horizontal offsetting, or at least bending, of the axis of the structural high (see Fig. 1).

The amount of vertical displacement of the faults varies widely. The greatest amount of displacement is reported in Kentucky in the southeast corner of the Smithland quadrangle (Amos, 1967) and in the southwest corner of the Burna quadrangle (Amos, oral commun., 1971). At the locality in the Burna quadrangle, sandstone of the Caseyville Formation of Pennsylvanian age is next to the Fort Payne Formation of Early Mississippian age. The general thickness of the Mississippian rocks above the Fort Payne is about 2,400 feet; hence, the minimum total displacement would be 2,400 feet. Considering that the Fort Payne is about 600 feet thick and the Caseyville is a few hundred feet thick, displacement might

be as much as 3,000 feet. In general, displacement is much less, commonly ranging from a few feet to a few hundred feet.

Little information is available regarding the amount of fault displacement in the subsurface below depths of 1,000 feet. A few drill holes in the Crittenden Springs and Commodore areas of Kentucky indicate that the amount of displacement at depths of nearly 2,000 feet below the surface is about the same as that at the surface.

Field evidence suggests that at least some and probably most of the major northeast-trending faults are younger than Hicks dome and the mafic dikes, and, therefore, are post-Early Permian in age. The major displacement along these faults may have been completed by middle Cretaceous time, although some movement has continued through Cretaceous and Tertiary time to the present (Rhoades and Mistler, 1941; Ross, 1963; McGinnis, 1963; Amos, 1967).

Locally some fault movement may have started during Early Pennsylvanian time. For example, in the northern part of the Golconda quadrangle, the lowermost Pennsylvanian Lusk Member of the Caseyville Formation in an oil test within the Rock Creek graben is about 130 feet thick, whereas the unit is only 50 feet thick where exposed along the eastern margin of the graben (Amos, 1966). Possibly the easterly thinning and westerly thickening are due, respectively, to movement and graben fill that began in Early Pennsylvanian time.

CHARACTERISTICS OF ORE BODIES

Most fluorspar ore bodies occur either as steeply dipping to vertical vein deposits along faults or as very gently dipping to nearly horizontal bedding-replacement deposits along certain stratigraphic horizons in limestone of Late Mississippian age (Fig. 4). Numerically, the known bedding-replacement deposits consist of probably less than a quarter of the total number of deposits; most of the deposits are veins. A few deposits, especially in Illinois, are made up of a combination of vein and bedding-replacement-type ore and so-called gravel deposits that resulted from concentrations of fluorite in residuum above vein deposits. Disseminated fluorite is present in the breccias of Hicks dome as deep as the Middle

Ordovician (Brown and others, 1954). A related fluorite deposit cementing breccia has been mined at the Rose mine near Hicks dome.

Veins

Most of the vein ore deposits are along northeast-trending faults, although a few veins are along northwest- and north-trending fissures or faults that are in places occupied by mafic dikes. The distribution of mineralized areas is shown in Figure 2. Mines are shown by Heyl and others (1965, pl. 2).

The fluorspar veins commonly are fissure fillings along faults and in fault breccia, accompanied by replacement of vein calcite and some limestone wall rock. A typical vein is lenticular, pinches and swells erratically, and is commonly a mixture of fluorite with highly variable quantities of calcite and country-rock fragments. Locally, the vein may be either entirely calcite or fluorite. Commonly, contact with vein walls is sharp; however, at places, veinlets of fluorite and calcite extend a few hundred feet beyond a vein into slightly broken wall rock. In many veins, sphalerite, galena, and barite are accessory minerals; in a few veins they are major constituents. A few veins of sphalerite and pyrite without fluorite have been productive, and a few barite veins are known.

The fluorite varies from fine and medium crystalline in small, commonly purple, veinlets to coarsely crystalline in commonly brown, white, or colorless, more massive veins. In many places, the veins are complexly brecciated and/or sheeted. Rude banding parallel to vein walls is present locally. Shaly fault gouge, presumably dragged in along the faults from shale units of the Chesterian Series, is common in places.

Width of most veins averages 3 to 10 feet (Hardin and Trace, 1959; Trace, 1962b), although a width of as much as 45 feet is reported (Grogan and Bradbury, 1968, p. 379). Length of mined ore shoots commonly ranges from 200 to 400 feet, although in many places, particularly in the Rosiclare area of Illinois, greater lengths are common. The average height of ore shoots is 100 to 200 feet, although ore shoots extending from the surface to a depth of nearly 800 feet were reported by Grogan and Bradbury (1968, Fig. 10).

Bedding-Replacement Deposits

Most bedding-replacement deposits and mines occur in the Cave in Rock, Ill., area, in the northeast part of the district (Fig. 2). Another area (and one operating mine) is present in Kentucky, beginning just southwest of, and across the Ohio River from, Rosiclare, Ill., and extending southward to near Joy, Ky. Probably about two-thirds of the mined bedding-replacement ore has been from the uppermost ore horizon near the top of the Renault or "Downeys Bluff" Limestone (Fig. 4).

The stratiform or bedding-replacement deposits are elongated bodies that trend northeastward and, less commonly, southeastward (Fig. 9). Most of these deposits "are localized along a network of fractures and minor faults parallel to and half a mile distant from the Peters Creek fault. . . ." (Grogan and Bradbury, 1967, p. 41-42). In cross section, they are crescentic or wedge shaped (see Figs. 10 and 11). A few pipe-like breccia·zones are mineralized (in places, with commercial-grade ore) and may be the conduits for ore solutions (Brecke, 1962, p. 511-514; Grogan and Bradbury, 1968, p. 393-394).

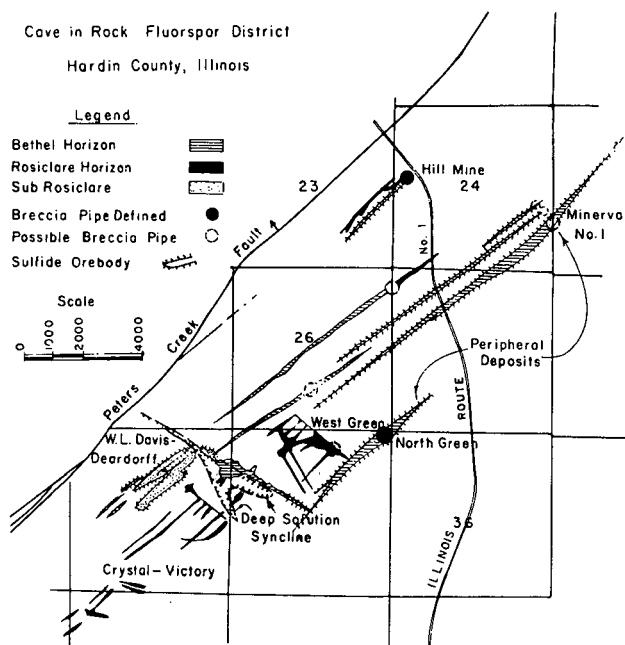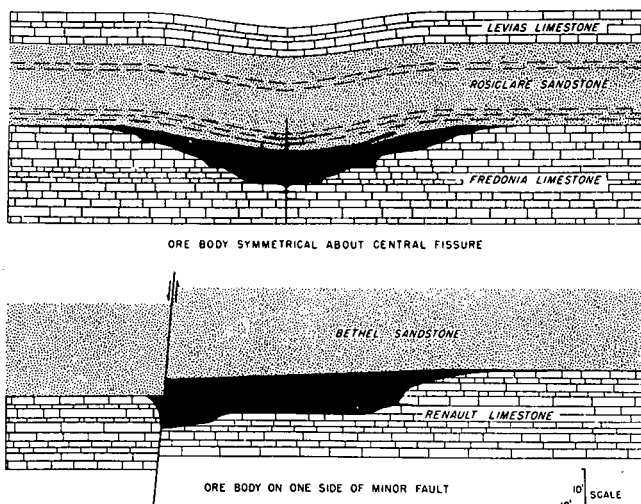The texture of the bedding-replacement deposits has been described by Brecke (1962, p.

Figure 10. Characteristic cross sections through stratiform deposits and enclosing strata. (Reproduced from *Economic Geology*, 1949, vol. 44, p. 608.)

515-525) as banded, imperfectly banded, and breccia. The imperfectly banded and breccia types constitute most of the deposits.

The ore bodies are commonly 50 to 200 feet wide and 5 to 20 feet thick; the length is highly variable, from 200 feet to 2 miles. The distribution of the mineralized trends is shown in Figure 9.

The bedding-replacement deposit being mined in Kentucky is believed to be approximately 2 miles long and 150 to 250 feet wide. It has an average thickness of 7 feet and contains about 30 percent CaF_2 and small quantities of zinc and barite (J. S. Tibbs, oral commun., 1971).

Depth of Ore

The deepest mined fluorspar is 800 to 900 feet below the surface in the Fairview mine in the Rosiclare area, Ill. (Grogan and Bradbury, 1968, p. 380). The deepest mine in the Kentucky area is about 700 feet (Dyer Hill mine for fluorspar and Hutson mine for sphalerite). Several holes drilled in the Rosiclare area (Muir, 1947) have intersected the veins more than 1,300 feet below the surface, but the veins at that depth are dominantly calcite and wall-rock fault breccia. A few deep holes drilled in Kentucky to depths of almost 2,000 feet have penetrated similar calcite veins.

Grade of Ore

The average grade of ore mined from the deposits has varied. Thirty years ago, the ore mined

Figure 9. Cave in Rock fluorspar district, Hardin County, Ill. (Reproduced from *Economic Geology*, 1967, vol. 62, p. 381.)
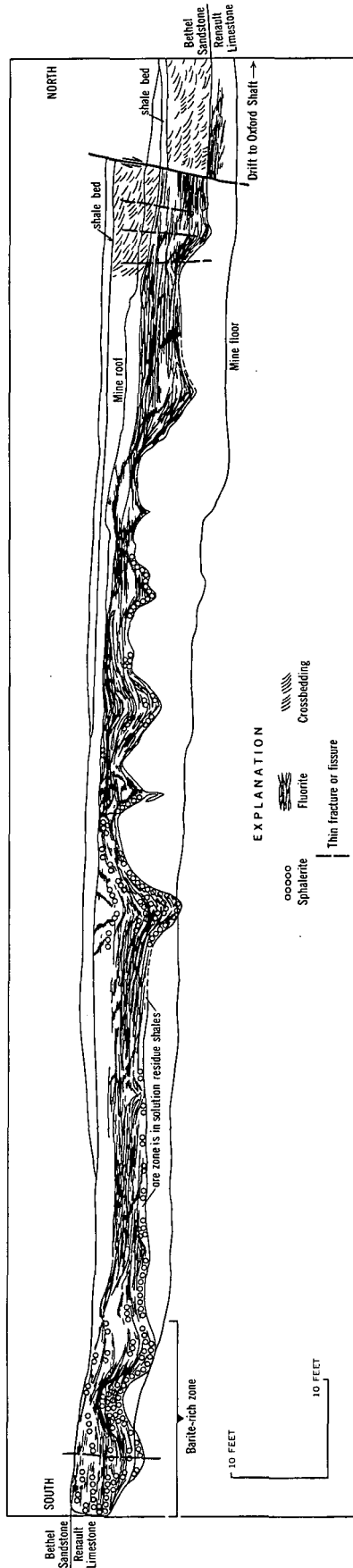
Figure 11. Cross section, Oxford mine, southern Hardin County, Ill. South ore body, facing west at shaft drift. (Courtesy M. R. Brock and A. V. Heyl.)

commonly contained at least 45 percent CaF_2, but gradually the ore cutoff grade has dropped and now is probably 25 to 40 percent CaF_2. Various factors have influenced the ore grade, such as the selling price of the finished product, the amount of byproduct zinc and lead (see below), and also the varying costs of mining, which are determined primarily by type of deposit and in part by mine depth, amount of water, and degree of stability of mine walls or roof.

The sphalerite, galena, and barite content of the mined veins and bedding-replacement deposits varies erratically. A substantial number of deposits, however, contain an average of about 2 to 3 percent zinc and $\frac{1}{2}$ to 1 percent lead. Some contain almost none or only negligible quantities of these minerals. At the other extreme, a few deposits are dominantly sphalerite or barite, with little or no fluorite, and may contain as much as 15 percent zinc and 30 to 40 percent barite. Rarely, galena is the dominant mineral.

The uppermost ore horizon of the bedding-replacement deposits, although the largest producer among the bedding-replacement deposits, is characterized by a lower average content of CaF_2 and Pb but is higher in Zn and its contained germanium and cadmium than the other two principal ore horizons (see Fig. 4). Cadmium is reported by Grogan and Bradbury (1968, p. 384) to average 1 percent in zinc concentrates from an Illinois bedding-replacement deposit. The galena in the Illinois part of the district contains as much as 1,000 ppm silver; that in the Kentucky part contains much less, 5 to 45 ppm (Hall and Heyl, 1968, p. 656).

Mineralogy

Quantitatively, the principal minerals in the vein deposits are calcite and fluorite. In places, minable deposits of only sphalerite or barite are present, although more commonly the sphalerite, barite, and galena occur in small quantities with the fluorite. Minor quantities of quartz, ferroan dolomite, pyrite, marcasite, chalcopyrite, and locally the zinc, lead, or copper alteration products (cerussite, pyromorphite, smithsonite, hemimorphite, greenockite, cuprite, and malachite) are present. Celestite occurs in one locality in Kentucky (Hardin and Thurston, 1945).

The vein and bedding-replacement deposits contain essentially the same suite of minerals. The principal difference is in the quantity of calcite, which is very abundant in the vein deposits and common, although not abundant, in the bedding-replacement deposits.

Fluorite is the principal mineral in the bedding-replacement deposits. Sphalerite, galena, and barite are locally very abundant but in places they are uncommon. Small quantities of calcite and quartz are persistent. Coarse quartz, however, is so abundant in a few deposits, such as the southwest end of the Deardorf mine (Illinois) that it prevents profitable mining. Ferroan dolomite is an abundant gangue mineral in the walls of most bedding-replacement ore bodies and occurs in small fissure veins in the Oxford mine (Illinois). Witherite occurs in such quantities in one Illinois orebody that it made concentration of fluorite difficult.

Chalcopyrite, marcasite, pyrite, witherite, strontianite, smithsonite, cerussite, malachite, bitumen, and pyromorphite have been reported by Grogan and Bradbury (1968, p. 384-385). Park (1967) reported that bravoite and vaesite occur in very small quantities locally in Illinois.

According to Hall and Heyl (1968), the fluorite in the district is remarkably pure except that found in breccias at Hicks dome which contains abundant rare-earth elements. Sphalerite of the district contains rather high amounts of cadmium, germanium, and gallium. Galena here contains as much as 1,000 ppm silver and antimony; the highest silver concentration is around Hicks dome, with lesser quantities outward.

The paragenesis of vein and bedding-replacement deposits appears to be similar. Of the more abundant minerals, the time of most calcite emplacement was earliest and was overlapped and followed by emplacement of fluorite. Some calcite is a late mineral. Sphalerite and galena emplacement generally appears to overlap and follow fluorite, and barite is the youngest main mineral. Hall and Friedman (1963, p. 891) reported in more detail on the paragenesis of the Cave in Rock deposits (Fig. 12).

Depositional-temperature studies by Freas (1961) and by Grogan and Shrode (1949), who used a method based on the disappearance of
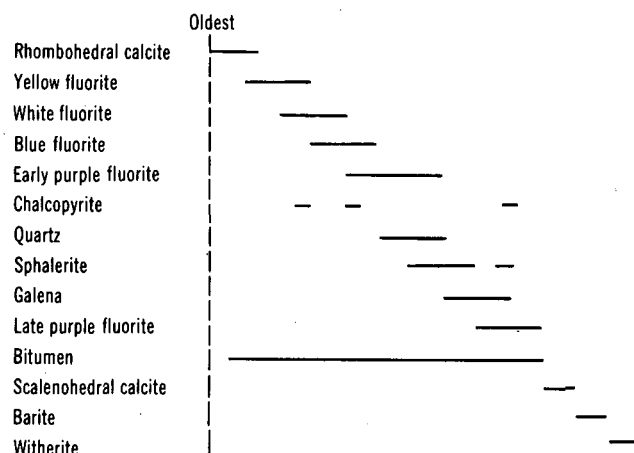

Figure 12. Paragenetic sequence in the Cave in Rock district, Illinois. (Reproduced from *Economic Geology*, 1963, vol. 58, p. 891.)

vapor bubbles in fluid inclusions, indicate a range of 90° to 140°C.

The composition of fluid inclusions in the ore and gangue minerals of the Cave in Rock area has been studied by Hall and Friedman (1963), who reported that the general composition of the fluid inclusions suggests that the fluorite was deposited from a concentrated Na-Ca-Cl brine, probably of connate origin, to which F has been added. Fluid inclusions in quartz, however, contain smaller concentrations of solids than do other gangue minerals and have a higher ratio of K/Na, Ca/Na, Cl/Na, and SO_4/Na, and a lower relative deuterium concentration. Possibly part of the fluids in the quartz period of deposition and the fluorine were derived from magmatic water.

Zoning

No apparent district-wide zoning of the fluorite, sphalerite, and galena has been reported. Brecke (1964a) suggested that barite is more common on the fringes of the district, but the relative abundance of barite in the Lola, Ky., area obscures the broad picture.

Heyl (1969) suggested a zonation pattern for the occurrence of silver and antimony in galena around Hicks dome (see also Heyl and others, 1966) and a systematic change in lead isotopic ratios for the area extending from Hicks dome southeastward into Kentucky.

Age

Accurate dating of the age of mineral deposition here is difficult. Stratigraphic relations indicate that the minerals were deposited after the Lower to Middle Pennsylvanian rocks were laid down. To the writer's knowledge, no fluorite has been found along faults where at least one fault wall is of Cretaceous or younger age. Thus, the age of mineralization is post-Early or Middle Pennsylvanian and pre-Late Cretaceous.

The fluorspar, on the basis of field relations, is younger than the mafic rocks and the major northeast-trending faults. These faults are probably younger than the mafic rocks, as no mafic rock is known along any of these faults. The mafic rocks have been dated isotopically as Early Permian; thus, both the major faults and fluorspar are post-Early Permian.

Heyl and Brock (1961, p. D6) reported a lead-alpha age of 90 to 100 million years (middle Cretaceous) for the monazite found near the surface at Hicks dome. If this is a valid determination (see below), and if the monazite and fluorite are of the same approximate age, as perhaps suggested by the relative abundance of rare earths in the fluorite near Hicks dome, then the age of the fluorite could be middle Cretaceous, a theory that does not conflict with known stratigraphic relationships.

Heyl (written commun., 1972), however, suggested that the lead-alpha date on the monazite is so open to question because of the material available that it should be discarded. Earthy monazite (and florencite), strikingly similar to the earthy Hicks dome monazite (and florencite), was described from Magnet Cove, Ark., by Rose and others (1958); they believe that the Arkansas monazite is a secondary product of weathering of rare-earth-bearing apatite. Fluorapatite has been identified by X-ray analysis by the writer in the mafic rocks of Kentucky, and apatite is present in some of the Hicks dome breccias. If the monazite is secondary, its value in dating the deposits is reduced considerably.

On the other hand, W. C. Overstreet (oral commun. to A. V. Heyl, 1968) has disagreed with Rose and others and does not believe that weathering-product monazite exists and that the composition (i.e., enrichment in yttrium and thorium) indicates a primary monazite derived from the mantle.

CONCLUSIONS

Ore Controls

The general location of the Illinois-Kentucky district may be structurally controlled by the intersection of northeast-trending faults of the New Madrid system (Fig. 6) with a large northwest-trending structural uplift, northwest-trending mafic dikes, and the 38th-parallel lineament. This east-trending lineament of igneous activity described by Snyder and Gerdemann (1965) and by Heyl (1972) passes through the district and is intersected by the fault systems.

Faulting was the primary factor within the district that controlled location of ore deposits, particularly vein deposits. Faults served as solution channelways for ore and provided space for deposition of ore bodies. Fractures and minor faults apparently were also significant factors in the localization of the bedding-replacement deposits, although their control on the shape of these deposits is somewhat less obvious than on vein deposits. Strata with low permeability, breccia pipes, and unconformities have been suggested as factors that localized bedding-replacement deposits (Brecke, 1962; Grogan and Bradbury, 1968).

Exploration and identifying individual vein deposits that contain minable fluorspar are costly and difficult because the veins contain highly varying quantities of calcite and fluorite. So far as the writer is aware, there are no guides to predict the calcite/fluorite ratio of a given vein prior to subsurface exploration.

One broad factor and a few more specific ones that might exercise some control of vein widths along the faults have been suggested by Grogan and Bradbury (1968), Thurston and Hardin (1954), and Trace (1954, 1962b). For example, most of the ore has been mined from veins where at least one wall, and commonly both walls, include the Cypress, Paint Creek (Ridenhower), Bethel, Renault, Ste. Genevieve, and St. Louis Formations of Mississippian age. The combined thickness of these units is about 1,000 feet. Possibly this stratigraphic control was effective because these units are dominantly competent and massive in contrast to the units of post-Cypress age which contain

many beds of incompetent shale, siltstone, and thin-bedded sandstone. Openings formed by faults where the walls are composed of Cypress Sandstone or older rocks probably remained open and received vein fillings; incompetent shaly material would less likely be dragged into and fill the fault zone. Also, the faults may steepen in dip where they intersect the more competent beds; this local steepening along normal faults could have allowed more space for mineral deposition. Similarly, where competent beds are involved, the total displacement of the fault system is taken up by many faults, thus creating more space, rather than by a few faults that created less space and steeper drag-folded walls, as in places where post-Cypress units are involved.

The amount of fault displacement may have influenced vein width. Thurston and Hardin (1954, p. 98) suggested that "extreme dislocation may produce excessive breccia and fault gouge." Perhaps a displacement of 25 to 500 feet was optimum for wide veins, as suggested by·Grogan and Bradbury (1968, p. 390-392).

A change in the general strike of a fault system may influence the location of deposits. Possible examples include, in Kentucky, the Babb area (Trace, 1962a) and Dyers Hill area (Amos, 1967) and, in Illinois, the Rosiclare area (Baxter and Desborough, 1965; Amos, 1965).

The spatial relation of mafic dikes to zinc deposits and fluorspar deposits having substantial byproduct zinc and lead is well known. This type of metallic sulfide mineralization may occur either along northwest- or north-trending faulted mafic dikes or along northeast-trending faults that are near mafic dikes. A deposit that contains abundant sphalerite and is rather close to a mafic dike was recently discovered in Livingston County, Ky. (Mining Record, Denver, Colo., Dec. 23, 1970).

Brecke (1967, p. 387) thinks that zinc sulfide deposition may be related to the iron sulfide of the mafic rocks. Oesterling (1952, p. 332) suggested that sphalerite was deposited where dikes were offset by faults after deposition of fluorite. According to Hardin (1955, p. 23), "the distribution of sphalerite is controlled to some extent by the cross and subparallel faults" of the fault zone; thus he implied late-stage faulting.

Sequence of Events and Genesis

The sequence of events and genesis of the Illinois-Kentucky fluorspar district has been discussed by Amstutz and Park (1967), Brecke (1962, 1964b, 1967), Brown (1970), Grogan and Bradbury (1968), Hall and Friedman (1963), Hall and Heyl (1968), Heyl and others (1965), Heyl (1969), Oesterling (1952), Park and Amstutz (1968), and Snyder and Gerdemann (1965). There is no consensus of opinions. Most geologists consider the deposits to be epigenetic; Amstutz and Park (1967) consider them to be syngenetic.

The exact timing of events and the origin of many of the unusual geologic features of the district are debatable. However, as a result of considerable research and field mapping in the last two decades by the Illinois State Geological Survey, the U. S. Geological Survey in cooperation with the Kentucky Geological Survey, and by several mining company geologists, much has been added to the geologic knowledge of the district.

Many of the structural and mineralogical events must have overlapped and recurred, thus confusing and frustrating many a geologist! In general, however, the geologic history can be divided into three broad phases, all probably occurring principally within the interval of post-Middle Pennsylvanian to pre-middle or Late Cretaceous. The oldest events were the structural arching and formation of Hicks and Tolu domes, the intrusion of. mafic dikes and sills, and the formation of breccias. According to Zartman and others (1967), these events appear to be approximately Permian in age. Next came most of the movement along the northeast-trending faults, followed by mineral deposition.

The deposits are considered by most geologists (Brown, Grogan and Bradbury, Heyl and associates, and the writer) as epigenetic, the ore elements being carried by hot connate water, which was heated by deep-seated igneous activity, upward along the faults to the present locations. At least some of the ore elements presumably were contributed to connate water by deep-seated igneous activity. Heyl (oral commun., 1972) and Hall and Friedman (1963) suggested that much of the calcite, dolomite, silica, and even the lead, zinc, and barium (but not fluorine or silver) may

have been derived from the connate brines and/or the rocks through which they passed.

Amstutz and associates suggested a syngenetic origin, and Brecke suggested that warm connate water picked up the ore elements from the sediments and moved them laterally into the district from the southwest, without recourse to igneous activity.

Potential

The imminent death of the fluorspar district has been predicted verbally for many years—even in 1942, when the writer first worked in the area. Although no comprehensive survey of fluorspar reserves has been made since 1956 (Fluorspar Reserves of the United States Estimated, press release, Office of Minerals Mobilization and Geological Survey, Nov. 23, 1956), a brief survey in the district by the author suggests that under 1971 economic conditions and continued current production, reserves are still substantial and probably adequate for at least 15 to 20 years. They are by far the largest fluorspar reserves in the United States, far surpassing any other district or region.

New finds of near-surface "gravel" deposits of fluorspar probably will be rare, and results from deep (more than 1,000 feet) exploration have been only slightly to moderately encouraging. The very large number of faults within the district not *adequately* tested at intermediate or, even in places, shallow depths, however, suggests to the writer that the district will be a source of fluorspar for many years. Currently, exploration is increasing, and several new discoveries of ore have been made in the last few years.

The fluorite occurrences in the breccias around Hicks dome currently are too low grade to mine. Under more favorable economic conditions and with recovery of the byproduct minerals, large-scale mining of these breccias might be undertaken some time in the future.

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STRUCTURE OF THE FAULT SYSTEMS IN THE ILLINOIS-KENTUCKY FLUORSPAR DISTRICT

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ABSTRACT

The Illinois-Kentucky fluorspar district is a gentle arch broken by north-east-trending fault systems. The fault systems are complex zones of step, antithetic, and cross faults between major horsts and grabens. The faults are predominantly normal and have dips ranging from 45 to 90 degrees. Vertical displacements range from a few feet to over 1,500 feet. The cumulative heave components of the normal faults indicate that the district has been extended about 1 mile in a northwest-southeast direction. Basement spreading related to minor rifting along the New Madrid fault zone is the probable cause of the crustal tension and gravity collapse. As the major grabens moved downward in a keystone manner to fill the voids, minor blocks broke loose along the edges creating the complex fault systems. The minor blocks were subject to both gravity movement and the downward drag of the grabens.

The structure of the district is further complicated by strike-slip movement. The magnitude of the strike-slip faulting is difficult to measure, but it is probably minor in comparison to that of the gravity faulting.

INTRODUCTION

The Illinois-Kentucky fluorspar district is a gently arched, block-faulted area in the deepest part of the Illinois basin. The block faulting is of the horst-and-graben type. The faults are predominantly normal and have northeasterly strikes. The term "fault system" as commonly used in the fluorspar district refers to wide zones of multiple faulting between horst and graben blocks. For example, the Moore Hill graben in Kentucky is bounded on the northwest by the Moore Hill fault system and on the southeast by the Claylick Creek fault system. The fault systems vary from a single fault to complex zones of step, antithetic, and cross faults as much as 1,500 feet wide. The vertical displacements between the horsts and grabens are commonly 500 to 1,500 feet, with a maximum of about 3,000 feet.

The vein-type deposits of fluorspar are usually along faults in the northeast-trending fault systems. Some economic deposits of fluorspar, and especially zinc, are found along north- to northwest-trending faults of minor displacements. The latter are usually referred to as "dike faults" because some of these faults have been intruded

by basic dikes. This paper will deal primarily with the structure of the northeast-trending fault systems.

MAJOR STRUCTURAL FEATURES

Figure 1 is a composite from many published and unpublished sources. It shows the prominent structures in and around the fluorspar district. The Cretaceous and younger formations are omitted because most of the faulting predates the Cretaceous and is masked by it.

The Shawneetown-Rough Creek fault zone along the northern edge of the district is described as a high-angle reverse fault. It is considered by some geologists to be a thrust fault and by others to be a wrench fault. Heyl (1972) related this structure to the 38th parallel lineament, a major basement lineament stretching from the Appalachians to the Ozarks, and possibly to the Rockies.

The New Madrid fault zone in the Mississippi embayment projects northeastward through the Illinois-Kentucky fluorspar district to the faults along the Wabash River. Heyl and Brock (1961) viewed the northeast-trending faults of the fluorspar district and the Wabash River faults as the
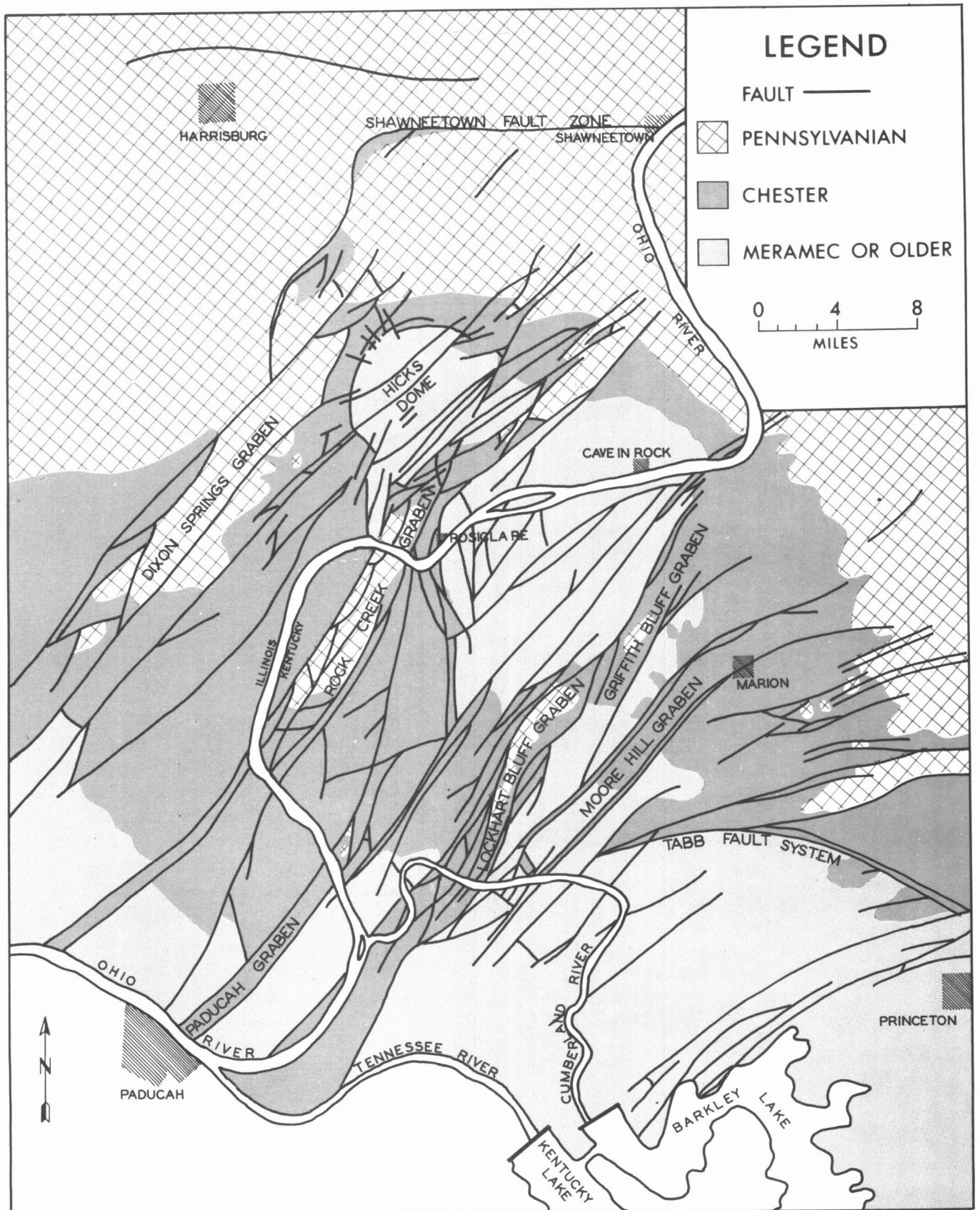
Figure 1. Prominent structures in and around the Illinois-Kentucky fluorspar district. Compiled from many published and unpublished sources.

New Madrid fault zone. The subsidence of the embayment area, the block faulting of the fluorspar district, and the igneous intrusions along this lineament are suggestive of incipient rifting.

Hicks dome, described by Brown and others (1954) as a cryptovolcanic structure, is near the intersection of the 38th parallel lineament and the New Madrid fault zone. The dome is about 9 miles in diameter and has 4,000 feet of structural relief. Diatremes with sedimentary and igneous breccia are found in the dome.

Basic igneous dikes and sills are found in the fluorspar district and in the coal fields north of the Shawneetown-Rough Creek fault zone. The dikes are in fracture zones that trend slightly west of north.

Except for the locally disturbed uplift at Hicks dome, the axis of the district arch is nearly north-south from the Tolu dome to Kuttawa. The arch is broken by the block faulting, and the crest is offset from one block to the next. The offset is not consistently to the right or the left.

Excluding the unusual structure at Hicks dome, the district arch is 25 to 30 miles wide and has about 2,000 feet of structural relief. The arch is a very gentle structure, and the formations have low dips except for locally tilted fault blocks and drag folding along the faults.

The major graben blocks generally trend northeastward, but some change direction locally; some are discontinuous, or offset. Some of the grabens hinge within the district, and most are hinged, or nearly so, at the edge of the district. The Rock Creek graben changes sharply in direction from N.30°E to N.55°E. near Rosiclare, Ill. It hinges in the edge of the district arch north of Cave in Rock. Mapping of sub-Cretaceous units indicates that the Rock Creek graben has also lost most of its displacement before reaching the Ohio River a few miles north of Paducah. The Lockhart Bluff graben is offset from the Griffith Bluff graben. The Moore Hill graben hinges near the crest of the district arch, but the bounding fault systems continue to the southwest, each containing minor grabens within the fault systems.

DESCRIPTION OF THE FAULTS

The horst-and-graben structure of the district is indicative of extensional tectonics. The north-east-trending faults in the fluorspar district are predominantly normal. The average dip is 70 to 75 degrees which produces about 100 feet of heave for each 300 feet of vertical displacement. The writer estimates that the cumulative northwest-southeast heave component of the normal faults of the district is roughly 5,000 feet. This indicates that the district was stretched about 1 mile. Excluding the Shawneetown fault zone, strike-slip faulting and other compressional features within the district are of minor structural consequence in comparison to the extensional features.

It is the thesis of this paper that multiple rupturing under tension and the subsequent gravity adjustments caused the northeast-trending block faulting in the Illinois-Kentucky fluorspar district. As the stretching progressed and the major grabens moved downward, many minor blocks broke loose along the edges to form the complex fault systems. These minor blocks within the fault systems have gravity movement along a series of step, antithetic, and cross faults (Hook and Winans, 1962). The actual faults thus created are usually wide zones of gouge, breccia, and vein minerals. Only rarely do the walls fit closely together, forming a clean-cut fault. The downward movement of the grabens produced both drag folding along the faults and rotation of the minor fault blocks within the fault systems.

Figure 2 is a schematic sketch of the horst-and-graben structure, illustrating a fault system with step faults on the left and a fault system with antithetic faults on the right. The chaotic nature of the faulting is omitted. Actually, both antithetic and step faults are usually present in a given fault system. The step faults have downthrown sides toward the grabens and the antithetic faults have downthrown sides toward the horsts.

Step Faults

The displacement in the fault systems is predominantly along step faults and their associated drag zones. These are apparently gravity faults which displace multiple fault blocks within the fault systems in a step-like manner from the horsts to the grabens. They are usually normal faults that dip toward the grabens, but local reversals of dip occur. In most cases, such reversals are
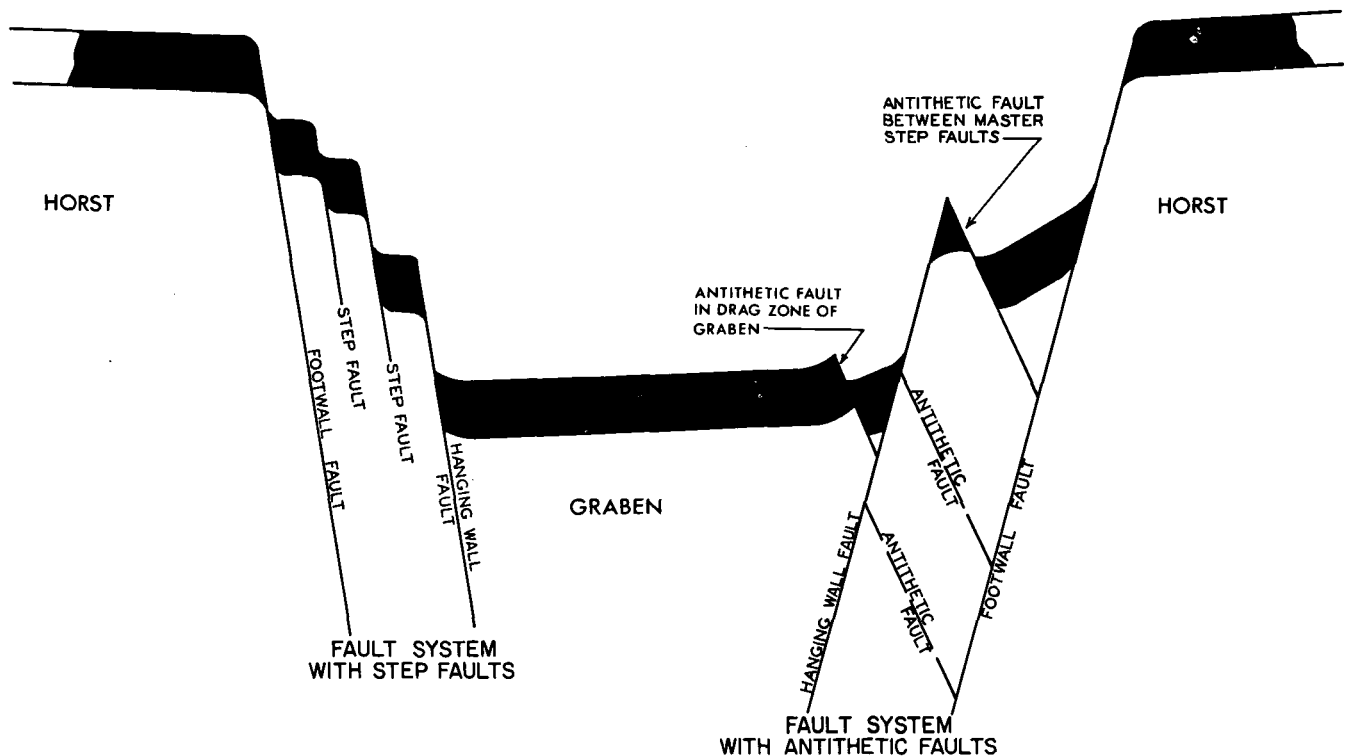
Figure 2. Diagrammatic sketch of a horst-and-graben structure, illustrating a fault system with step faults on the left and one with antithetic faults on the right.

along local segments of what is otherwise a steep-angle normal fault. The step faults usually dip from 60 to 90 degrees and, where reversed, are seldom more than 5 degrees from vertical. Both the strikes and dips along the step faults are undulating and can change as much as 15 to 20 degrees within a few hundred feet.

The fault systems in some places pinch down to what is essentially a single major step fault, but multiple step faults are the rule. A relatively common occurrence in the district is to find two master step faults forming the outer boundaries of a fault system. In these cases, the fault adjacent to the horst is locally termed the "footwall fault" and the one adjacent to the graben, the "hanging-wall fault."

Intervening blocks between two master step faults have been subjected to considerable drag which caused rotation toward the graben. Such blocks usually have yielded to additional fracturing and faulting. Caught in the forces of a couple between the up-drag on the footwall master fault and the down-drag on the hanging-wall master fault, both tension and shear fractures developed. Movement along the shear fractures

produced additional minor step faults, while movement along the tension fractures developed antithetic faults.

Antithetic Faults

The antithetic faults are usually found in the tilted blocks between step faults as previously mentioned, but they also occur in the drag zones of the major grabens. In either case they were developed along tension fractures dipping opposite to the bedding of the stratigraphic units. Due to local drag, the formations dip toward the graben while the antithetic faults dip toward the horst. The strike of the antithetic faults is generally parallel to the fault system. The antithetic faults usually have relatively low angles of dip, 45 to 65 degrees, whereas the step faults usually dip 60 to 90 degrees. The antithetic faults terminate downdip against step faults. The wedge-shaped blocks thus created are minor grabens within the fault systems.

The antithetic faults apparently developed in response to, and along with, continued movement on the master step faults. As the stretching of the district continued, gravity movement occurred

along the tension fractures between step faults, and also in the drag zones in the grabens. The gravity movement was augmented and possibly even initiated by the rotation of the formations toward the grabens.

In other words, the minor blocks between step faults were caught in the forces of a couple which caused rotation toward the graben. This developed tension fractures dipping away from the step faults. Further movement of the step faults initiated the movement on the tension fractures. Further stretching due to extensional tectonics permitted gravity movement on the antithetic faults.

The heave components of the antithetic faults augmented the heave components of the step faults in filling the voids created by the extensional tectonics. The step faults permitted the major grabens to partially fill the voids by a keystone type of movement, and the antithetic faults further added to the fill by dropping minor grabens within the fault systems. The remaining space was filled by the added volume created by fractured and brecciated rock and vein mineralization along individual faults. Two prominent examples of antithetic faults are the Blue Diggings vein at Rosiclare, Ill., and at the Davenport mine near Salem, Ky.

Figure 3 is a block diagram of the Moore Hill fault system at the Watson and Davenport mines. The fluorspar ore in these mines was localized along step and antithetic faults. The net vertical displacement of the Moore Hill fault system at this point (the stratigraphic displacement between the Moore Hill graben and the Salem Valley horst) is 600 feet; the cumulative heave is 360 feet. Figure 3 also shows cross faults, the third type of fault found in the northeast-trending fault systems.

Cross Faults

As the name implies, the strike of the cross faults is counter to the strike of the fault system. The cross faults are normal gravity faults resulting from differential downward movement in blocks which were caught between step faults or between a step and an antithetic fault. In addition to the cross faults within the intermediate blocks of the fault systems, some of the major grabens have had differential downward displacement which caused rupturing and consequent cross faulting.

In either the major grabens or the smaller fault blocks within a fault system, there is often a longitudinal component of tilting. Where this component of tilting is uneven, the blocks rupture along cross faults. Both the step faults and the antithetic faults may be terminated or be displaced by cross faults or vice versa. The longitudinal component of dip may also cause hinging along which step or antithetic faults may die out, but termination at cross faults seems to be more common.

Northwest-Trending (Dike) Faults

The basic dikes of the fluorspar district are along north- to northwest-trending faults. These faults have very little vertical displacement; apparently the movement was primarily strike slip as indicated by the slickensides. These clean-cut, northwest-trending faults with nearly straight strikes and dips are in sharp contrast to the undulating, chaotic faults of the northeast-trending fault systems.

Oesterling (1952) believed that the dikes along these northwest-trending faults are older than the northeast-trending block faulting, but that the zinc deposits along these structures were due to much later (post-fluorite) movement. The dikes are offset by northeast-trending faults. The dikes do not intrude the northeast-trending faults, but Oesterling (1952) found post-fluorite movement along the dike (northwest-trending) faults which displaced northeast-trending faults at the Hutson mine.

Strike-Slip Faulting

The northwest-trending (dike) faults seem to have predominantly strike-slip movement. Slickensides along the northeast-trending faults also indicate components of lateral movement. Bastin (1931) described slickensides along the nearly vertical Daisy vein at Rosiclare which are inclined from 10 degrees north to 80 degrees south. Slickensides with inclinations ranging from horizontal to vertical have been observed throughout the district. Thus, in addition to the gravity movement of the major grabens and the associated northeast-trending fault systems, there has also been a component of wrenching.
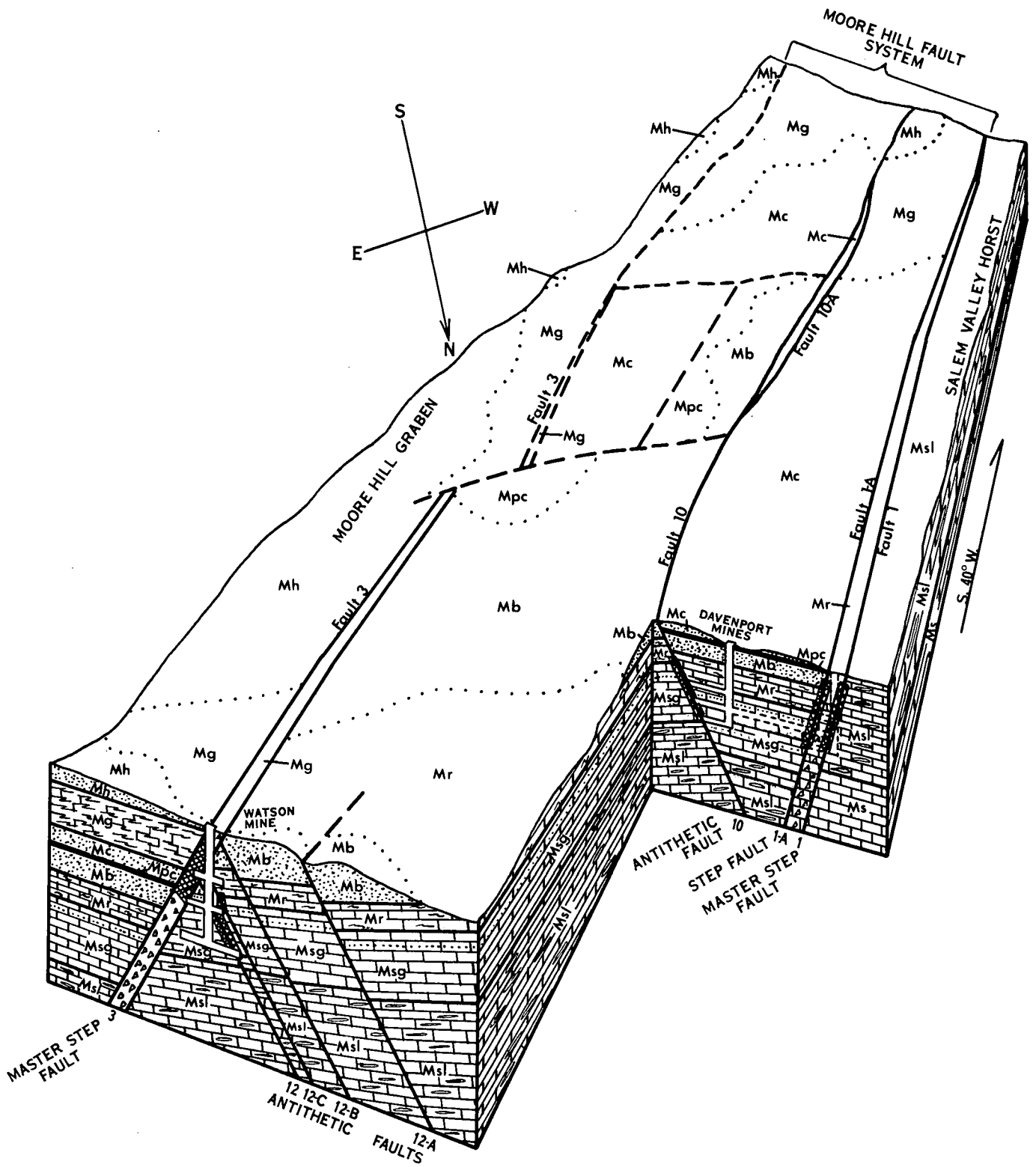
Figure 3. Block diagram of the Moore Hill fault system at the Watson and Davenport mines. Stratigraphic units are: Msl, St. Louis; Msg, Ste. Genevieve; Mr, Renault; Mb, Bethel; Mpc, Paint Creek; Mc, Cypress; Mg, Golconda; and Mh, Hardinsburg. Length of block, 3,500 feet; width, 1,700 feet.

The amount of strike-slip movement on the major northeast-trending faults is unknown. It is the writer's opinion that the strike-slip component of movement is relatively minor in comparison to the dip slip on the major fault blocks. A swarm of dikes extending intermittently from the Glendale area on the Commodore fault system southeastward to the Claylick fault system on the Salem quadrangle (Trace, 1962) crosses three major fault systems without appreciable lateral displacement.

However, some of the northeast-trending faults with minor vertical displacement are predominantly strike slip. The Gaskins mine in the Empire district on the west side of Hicks dome has predominantly horizontal slickensides and tension fractures indicating left-lateral movement. The vein splits into two segments in the central part of the mine but is otherwise a nearly straight, uncomplicated structure in comparison to the undulating veins along the gravity faults in the district.

Baxter and Desborough (1965) suggested that the relative importance of strike-slip and high-angle reverse faulting as compared to normal faulting in the fluorspar district has probably been underestimated. However, while strike slip is a factor to be considered seriously, I would also caution that it not be overestimated. In general, strike slip seems to be more of a factor in Illinois, closer to the 38th parallel lineament, than in the Kentucky portion of the district.

Both left-lateral and right-lateral movement have been observed in the Cave in Rock area of the district (Don Saxby, personal commun.). The minor faults associated with the bedded deposits are predominantly strike slip.

The relative importance of strike slip as compared to normal faulting needs further study. The study should also compare the relative amount of right-lateral movement to left-lateral movement. The role of the Shawneetown fault zone (the 38th parallel lineament) relative to the other faults of the district should be examined more closely.

ORIGIN OF THE FAULT SYSTEMS

The origin of the fault systems is speculative. A viable mechanism to explain the block faulting must be compatible with the structure of the existing fault systems and the gentle dips of the major blocks. It must account for the major dip-slip components including about a mile of cumulative heave.

Five tectonic mechanisms have been proposed in the literature, singly or in combinations, as the forces which created the block faults. Basically, the five mechanisms involve (1) expanding magma, (2) shrinking magma, (3) release of lateral compression from the southeast, (4) northwest-southeast extension due to southwest compression, and (5) strike-slip movement along the Shawneetown fault zone.

Expanding Magma

Weller (1927, p. 94) related the fault systems to extension and uplift during a deep-seated intrusion: "All of these faults are of the normal or tensional type, and have been formed by the stretching of this segment of the earth's crust." He related the basic dikes in the district to the intrusion.

Oesterling (1952) discounted this theory on the basis that the dikes are older than the block faulting. However, Oesterling's evidence does not preclude arching and extension due to a post-dike intrusion.

Of the five mechanisms, Weller's theory is the only one which proposes active tension. Other theories propose a component of tension as a byproduct of compressional forces.

Shrinking Magma

Heyl and Brock (1961) and Grogan and Bradbury (1968) suggested that the shrinkage of a cooling magma contributed in part to the block faulting. This implies that the shrinkage removed support and contributed to the collapse. However, would shrinkage of the magma not have tended to shrink the area of the overlying sediments also? How could shrinkage of the intrusion have produced the extensional characteristics of the normal faulting?

Release of Lateral Compression From the South

Weller (1940), Oesterling (1952), and Grogan and Bradbury (1968) suggested that relaxation of the compressive stresses which formed the Shawneetown fault zone contributed in whole or in part to the block faulting. Oesterling (1952, p. 329) added the opinion that ". . . in view of the

extensiveness and complexity of the faulting, the release of pressure was quite sudden, as might be expected to result from the Shawneetown-Rough Creek thrust faulting."

Some shattering could possibly result from the sudden release of compression as Oesterling suggested, but how could relaxation develop the extensional tectonic structures of the district? Unless the relaxation of compression was followed by rebound or withdrawal to produce tension, how could this mechanism produce the normal faults of the district? This theory calls for relaxation of compression; if tension is implied, it should be so stated.

Northeast-Southwest Extension Due to Southwest Compression

This theory proposed that the extensional tectonic features of the block faulting were the result of bulging when pressure was applied from the southwest. Brecke (unpub. ms.) states: "The forces producing the faults were apparently compressional from the southwest. Such forces tend to produce shortening of the crustal layers. Evidence of this shortening is found in three forms: folding, shearing, and overthrust. Thrust faulting and the arcuate faults of the Kentucky part of the district indicate overriding pressure from the southwest. The Shawneetown-Rough Creek fault is a high-angle overthrust and probably the largest relief feature of the system."

Except for steeper dips at Hicks dome and the drag folding and tilting near normal faults, the formations of the district have low dips. Had there been enough shortening in a northeast-southwest direction to produce the approximately 1 mile of northwest-southeast extension, the compressional structures should be more pronounced.

Strike-Slip Movement Along the Shawneetown Fault Zone

This theory proposes that the northeast-trending fault blocks were formed by left-lateral strike-slip movement along the Shawneetown fault zone. Heyl and Brock (1961, p. D-6) combined this theory with the shrinking magma theory as follows: "Subsequent cooling and shrinkage of the igneous rocks partly lowered the anticline. This action was combined with a compressive force-couple acting along the Rough Creek-Shaw-

neetown fault zone, which compressed and rotated the north end of the fold in a counterclockwise direction to develop the numerous northeast-trending fault blocks."

This theory proposes a considerable strike-slip component for the northeast-trending faults. To offset the anticlinal axis of the Tolu-Kuttawa arch to Hicks dome would require a cumulative strike slip of about 5 miles. Heyl and Brock (1961, p. D-6) indicate that a gaseous explosion took place on the apex of the structure to form the smaller dome (Hicks dome) and its diatremes. I agree with this proposed origin of Hicks dome except that the explosion probably occurred on the flank of the district arch rather than at the apex. With the latter interpretation, no rotation is required.

In the preceeding paper, Trace (this symposium) shows offset of the arch in both directions, not consistently to the left as would be the case if there were substantial left-lateral strike slip on the northeast-trending faults.

Other evidence against strike-slip movement of the magnitude indicated by this theory is that: (1) the basic dikes which probably predate the block faulting apparently have little offset along the northeast-trending faults, (2) drag folding in the district indicates predominantly dip-slip movement, and (3) the irregular, chaotic nature of the northeast-trending fault systems is more in keeping with gravity collapse due to tension than the organized, clean-cut nature of strike-slip faulting.

Later studies by Heyl (1972) indicate that the Shawneetown fault zone is part of the 38th parallel lineament which has right-lateral movement. Right-lateral movement on the Shawneetown fault zone would not produce the northeast-trending tension fractures with left-lateral movement as the earlier theory proposed. However, it would produce northwest-trending fractures with the general trend of the dike faults.

Discussion

Right-lateral movement on the 38th parallel lineament prior to the period of block faulting could have opened the northwest-trending tension fractures which were intruded by the basic dikes. Renewed periods of movement could have reopened these structures during the periods of

fluorite and sphalerite mineralization proposed by Oesterling (1952).

Movement along the 38th parallel lineament has probably been intermittently active since Precambrian time (Heyl, 1972). The major period of block faulting probably occurred about the close of the Paleozoic. Thus, torsional forces producing the northwest-trending (dike) faults and the strike-slip movement on the northeast-trending structures may have been active before, during, and after the period of block faulting. Such movements could have set the northeast-trending pattern and produced the later strike-slip slickensides found in the fault systems. However, it is my opinion that the major block faulting was primarily gravity movement due to stretching of the crust. Although the torsional forces were active over a greater period of time, the strike-slip movement seems minor in comparison to the dip-slip movement produced by the tensional forces.

The New Madrid fault zone (including the block faulting in the fluorspar district and the faults along the Wabash River) is suggestive of a zone of incipient rifting. Basement spreading due to a minor plate movement could have caused the igneous activity along this zone and the extensional tectonic structures in the fluorspar district. The extension may be due in part to a deep intrusion, as suggested by Weller (1927), which was associated with the rifting.

The major block faulting occurred between Pennsylvanian and Cretaceous times. The original horst-and-graben topography has now been largely reversed by erosion. The resistant massive Pennsylvanian sandstone remnants in some of the grabens now form the highest ridges in the district, while the St. Louis and Ste. Genevieve areas of the horsts form much of the present lowlands. However, some later movement has occurred as reflected in Cretaceous and possibly Eocene sediments (Ross, 1963). Both the New Madrid and Shawneetown fault zones are still active.

CONCLUSIONS

The major movement on the northeast-trending fault systems probably occurred during a relatively short period in post-Pennsylvanian time, but some minor movement has continued. The block

faulting was due to extensional tectonic forces which caused crustal stretching and gravity collapse.

Torsional forces have caused both right-lateral and left-lateral movement along some of the northeast-trending faults. The magnitude of this movement is mostly unknown but it is believed to be relatively minor in comparison to the normal faulting.

The northwest-trending (dike) faults are probably tension fractures related to right-lateral movement along the 38th parallel lineament. These fractures were opened prior to the period of block faulting when the basic dikes were emplaced, and reopened subsequent to the block faulting druing perods of fluorite and sphalerite mineralization.

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GEOLOGY AND HISTORY OF PENNWALT CORPORATION'S DYERS HILL MINE, LIVINGSTON COUNTY, KENTUCKY

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ABSTRACT

Pennwalt Corporation's Dyers Hill mine, located northeast of Smithland, Livingston County, Kentucky, was operated between 1956 and 1968. During this period it was one of the most important fluorspar mines in the Western Kentucky district. The ore, a vein-type deposit, consisted of clear, white, and brown fluorite with inclusions of galena and sphalerite. Mining was carried on between depths of 350 and 690 feet.

The Dyers Hill mine is located 3.5 miles northeast of Smithland, Livingston County, Ky., at an elevation of about 500 feet. It is reached by driving northeast from Smithland along U. S. Highway 60 for 4.5 miles and then traveling on a gravel road for another 1.2 miles to the shaft. The shaft location is shown on the 7.5-minute Smithland quadrangle topographic map. The area is one of small, highly eroded hills, with many small sandstone bluffs, lying between the Ohio River flood plain and the normal plateau, some 300 feet higher in elevation.

The rock formations are, for the most part, sedimentary and of Pennsylvanian and Mississippian ages; they are cut by many faults having throws of up to 3,000 feet. Most of these faults are normal and have northeasterly strikes; dips are from 70° to 90°. Intruded across this fault system are a series of basic igneous dikes which trend in a north to northwest direction. The Pennsylvanian rocks are all of a siliceous nature, with interbedded shales and coal. The Mississippian rocks are composed of interbedded sandstones, limestones, shales, and minor amounts of coal.

The faults, which in general trend from about N.15°E. in the western part of the area to about S.60°E. in the southeastern part, would have a combined length in the order of thousands of miles in the roughly 40 by 30 mile area that makes up the Illinois-Kentucky fluorspar district. The strike of the faults in the Dyers Hill area varies from about N.25°E. to N.60°E.

Many of the faults are scissor or "purse" faults; that is, they die out at one or both ends, with the maximum throw occurring at one end or in the middle. Where this diminishing of throw occurs, subparallel faults occur, opening up in the opposite direction to keep the overall throw about the same for long distances; the surface formations within any given fault block remain almost uniform.

The igneous dikes are narrow, being from a few inches up to perhaps 20 feet in width, but may be several miles long. They were apparently intruded at a slow rate, because in places they are composed of almost pure calcium carbonate which was dissolved by the intrusive mass and pushed ahead of it across the country rock.

Three types of ore deposits are found in the area: (1) gravel, or residual deposits, (2) manto, or replacement deposits, and (3) vein deposits. Vein deposits are the most common type, and this is the type that is found in the Dyers Hill mine. These vein deposits are the result of fissure filling by ascending pneumatolitic solutions from which the fluorite and other minerals crystallized at the correct conditions of temperature and pressure, when the elevation of a good host horizon was reached. In the Illinois-Kentucky area, if fluorspar is found in a vein, it will be found at the elevation of the Fredonia limestone. It may be found opposite other limestones; but if it is, it will also be found at the elevation of the Fredonia.

The ore is normally found in areas along the strike of a fault at the elevation of the Fredonia limestone, on one or both sides of the fault. The ideal case is at points where the throw of a fault almost, but not quite, offsets the Fredonia. Where this situation exists, a continuous vertical ore deposition of from 200 to 500 feet may be expected. Ore deposits are now found by diamond core drilling since virtually all of the deposits that are exposed at the surface have already been found.

Vein deposits are found by drilling angle holes of 45° to 60° from the hanging-wall side of the fault to intersect the vein at the elevation of the Fredonia limestone. In cases where the Fredonia is offset, it may be necessary to drill the structure at the elevation of the Fredonia on each side of the fault. Drill holes deviate as much as 15°, both vertically and horizontally; therefore, a good borehole survey is a must.

To date, three ore deposits have been found in the Dyers Hill area of Livingston County, Ky. Only one of these, the so-called "Number One" deposit, has been mined. It is with this "Number One" deposit that this paper is concerned.

The deposit was found by diamond drilling on the Frank O. Werner farm in March 1950. When four holes had been completed in the discovery area, a drilling program was set up to test the main branch of the Dyers Hill fault to the southwest toward the Ohio River, but without success. In the spring of 1951 a new program was set up to prospect updip to the northeast of the discovery point along the strike of the fault. The first hole cut 17 feet of high-grade fluorspar, sphalerite, and galena ore. Good minable ore was cut in 15 of the next 16 holes, covering a distance of 3,200 feet to the northeast. This drilling program was completed early in 1952. The main Dyers Hill fault was found to be mineralized with fluorspar for a distance of 4,200 feet overall, and varied from 1 foot to over 30 feet in width. It had an economic minable depth of about 400 feet.

At the surface, the northwest wall of the fault is Golconda limestone, and the southeast wall is Bethel sandstone. The average fault movement was about 235 vertical feet along the fault plane that has a dip of about 75° to the northwest.

A highly weathered igneous dike was found some 1,500 feet southwest of the shaft. Strike of the main vein was N.28°E. northeast of the dike, and S.47°W. southwest of the intrusive.

Two other areas of minable mineralization were found associated with the "Number One" deposit. The "L" vein, a mineralized tension fracture having little or no displacement, splits off the main fault some 400 feet southwest of the shaft and strikes S.70°W. for 1,500 feet, where the mineralization terminates in an open water-filled cavity, 300 feet long, containing a few limestone boulders. In this vein the ore extends only from 50 feet below the 350-foot level down to below the 690-foot level, where it becomes too narrow to mine. The ore in this vein ranges in width from 0.5 to 8 feet.

An antithetic fault dips through the main shaft at an angle of 75° to the southeast; this fault intersects the main vein at a depth of 500 feet and runs parallel with the main fault. Its southwest end abuts against the "L" vein. The ore cut in the shaft was 6 feet wide from a depth of 260 feet down to 320 feet; however, it had pinched to nothing at the 350-foot level and only opened up to about 15 inches at a depth of 400 feet. In order to protect the shaft, this ore was not mined.

The major components of the main vein were fluorite, calcite, shale, limestone, sandstone, fault gouge, and a narrow band of aragonite that practically filled the final void. In addition, there were minor concentrations of barite near the top of the economic mineralization, which occurred some 200 feet below the surface. The fluorite ore contained about 1 percent galena; southwestward from the main shaft the amount of sphalerite in the ore increased gradually to perhaps 3 percent in the vicinity of the dike. This sphalerite was normally concentrated along the hanging-wall side of the vein and in many places impregnated the first few inches of the hanging wall itself. The sphalerite concentrate contained almost 1 percent cadmium and 0.06 to 0.09 percent of both germanium and gallium.

The ore varied in width both horizontally and vertically; hard, clear to white fluorite, containing inclusions of galena with varying amounts of calcite, were predominant in the northeast end of the mine. This ore graded through brown

fluorite, containing galena and increasing amounts of sphalerite, to soft gouge-like material containing fluorite, galena, and sphalerite as the mine progressed to the southwest. The material in the last 1,200 feet at the southwest end of the mine was very soft, and the walls and back were difficult to hold. There was very little crystalline fluorite present in the mine; however, in some of the voids in the vein in the northeast end of the mine there were many dogtooth calcite crystals as much as 18 inches in length.

The ore in Dyers Hill mine was reached by a shaft, sunk in the hanging wall of the vein, 180 feet northwest of the fault outcrop; a dewatering well was drilled 27 feet southeast of the shaft. Levels were turned off from the shaft at 350 feet and 520 feet, with one more level at 690 feet, which was reached from the 520-foot level by a winze located 30 feet northwest of the shaft (Figs. 1-6).

The usual mining method was shrinkage stoping with free-floating cribbed manways at 150-foot intervals and loading shoots at 25-foot spacings. As the mine progressed to the southwest, increasingly incompetent walls were encountered. As a result, many other methods were tried. Some cut-and-fill stoping was done, and we also tried underhand stoping from sublevels. In the extreme southwest end of the mine, half-inch-thick pyramidal steel hoods, supported on 6-inch by 6-inch oak cribbing, were jacked up as the soft gouge-like ore was removed from above through sliding trap doors in the hoods. From the stope area, the ore was trammed to the shaft loading pockets, where measuring pockets were located, in 2-ton side-dump cars pulled by Mancha battery-operated locomotives on 18-inch gauge rails.

The decision to open Dyers Hill mine was made in 1954, and early in 1955 the access road was located and the dewatering well was drilled. The main shaft was started in August 1955, with completion to 350 feet, where the first level was turned off, in January 1956. The planned operating tonnage of 85 tons per day was reached in May of that year. In February 1958 a winze was started from the 350-foot level to prepare for the raising of the shaft from the 520-foot level to the 350-foot level. At this time the production was 165 tons of raw ore per day. The raise from the 520-foot level was started in January 1959 and completed in October of that year. At this time production was set at 210 tons per day and increased to 300 tons in March 1962. In May 1963 a winze was started 30 feet northwest of the shaft on the 520-foot level to open the 690-foot level. This was completed in November 1964. Daily production reached over 550 tons of raw ore per day in early 1965, and then began to decrease. The mine became unprofitable to operate and was closed in June 1968.
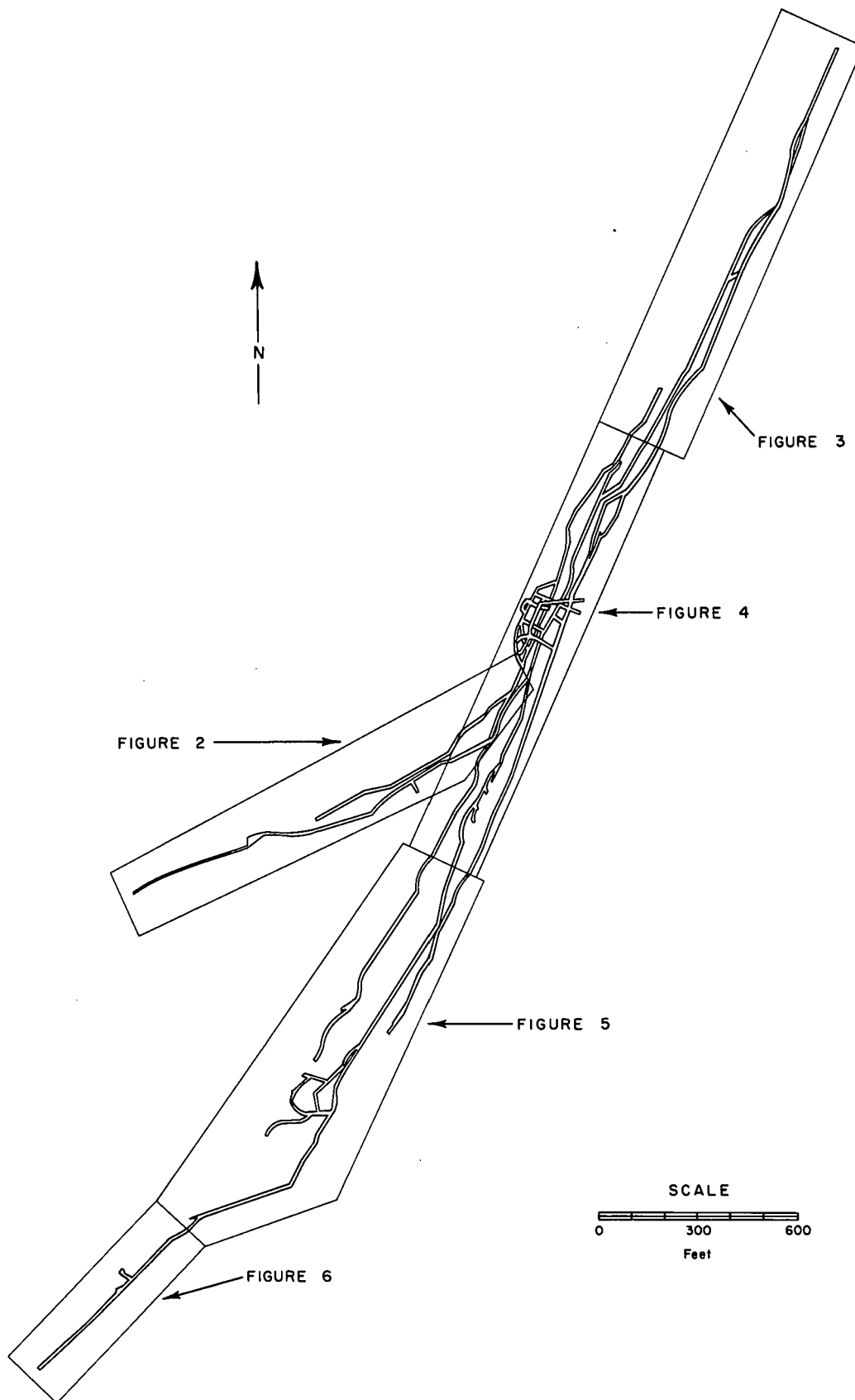
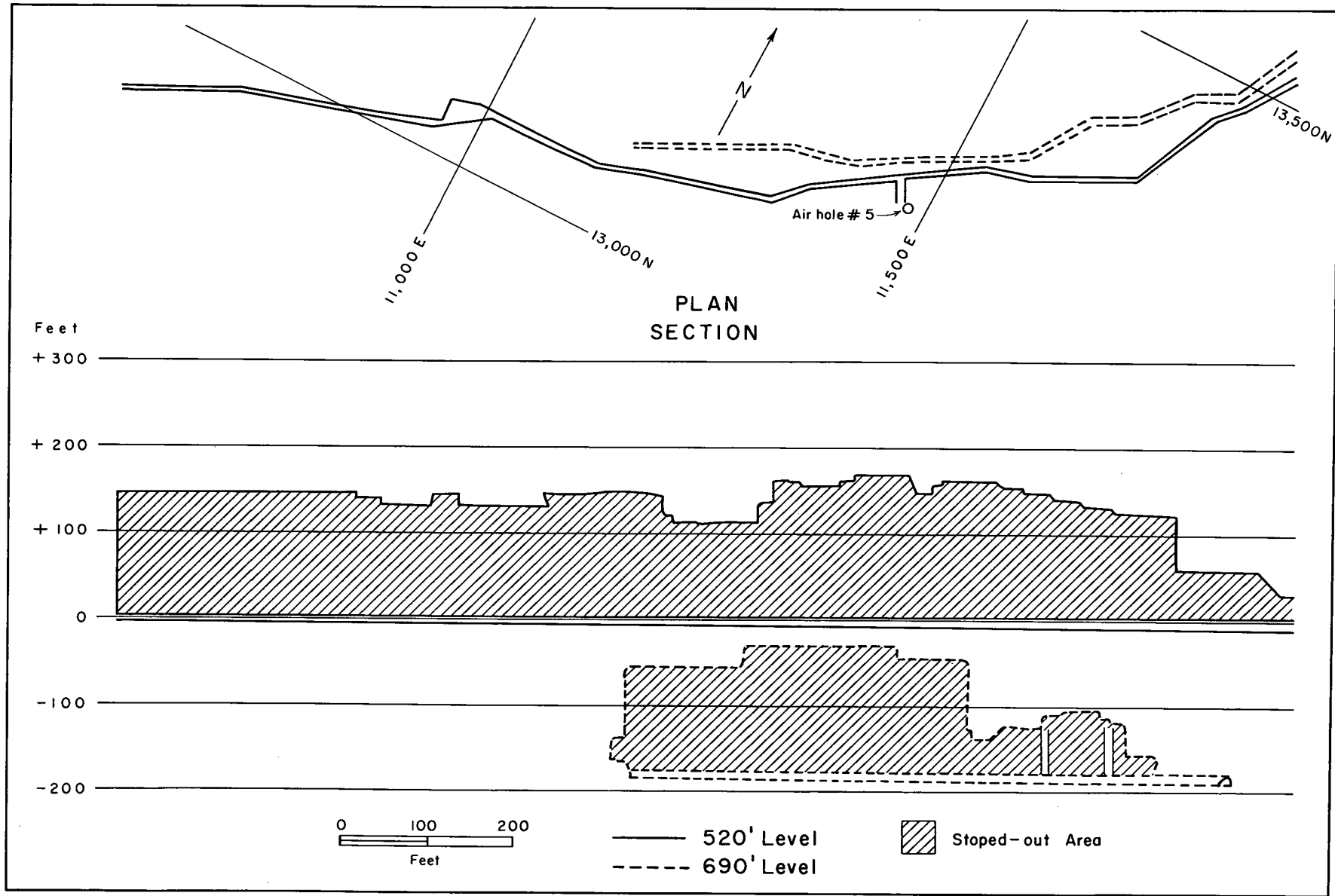Figure 1.   Plan of Dyers Hill mine. For further details see Figures 2-6.

PLAN
SECTION

Air hole # 5 →

11,000 E

13,000 N

11,500 E

13,500 N

N

Feet

+300

+200

+100

0

-100

-200

0   100   200

Feet

——— 520' Level

- - - - - 690' Level

▨ Stoped-out Area

Figure 2.   Plan and section of "L" fault section of mine.

PLAN
SECTION

Air hole # 6

14,500N

12,500 E

15,000N

Feet
+ 300

+ 200

+ 100

0

-100

-200

0   100   200
Feet

−·−·−· 350' Level
——— 520' Level
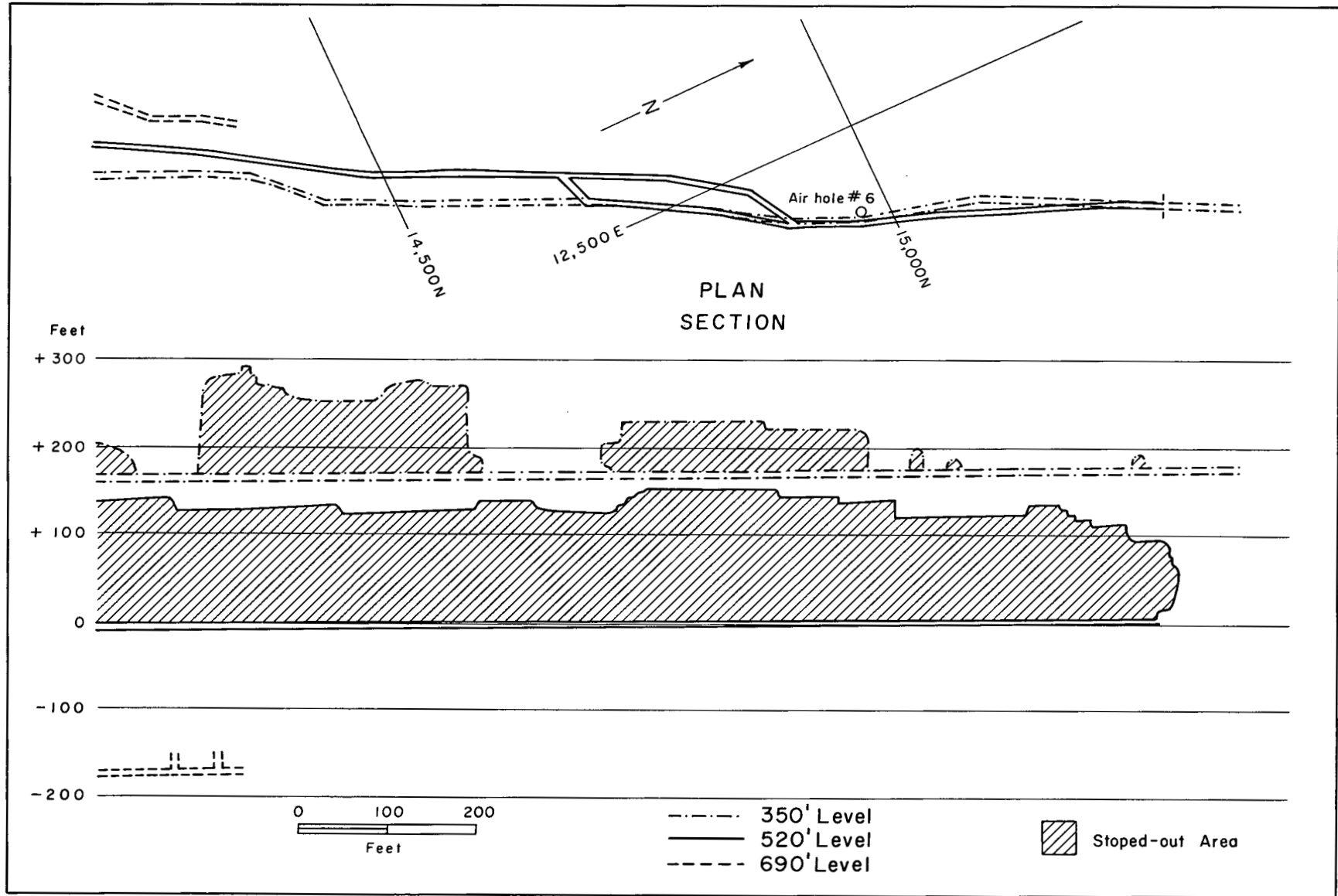- - - - - 690' Level

Stoped-out Area

Figure 3.   Plan and section of northeast end of mine.
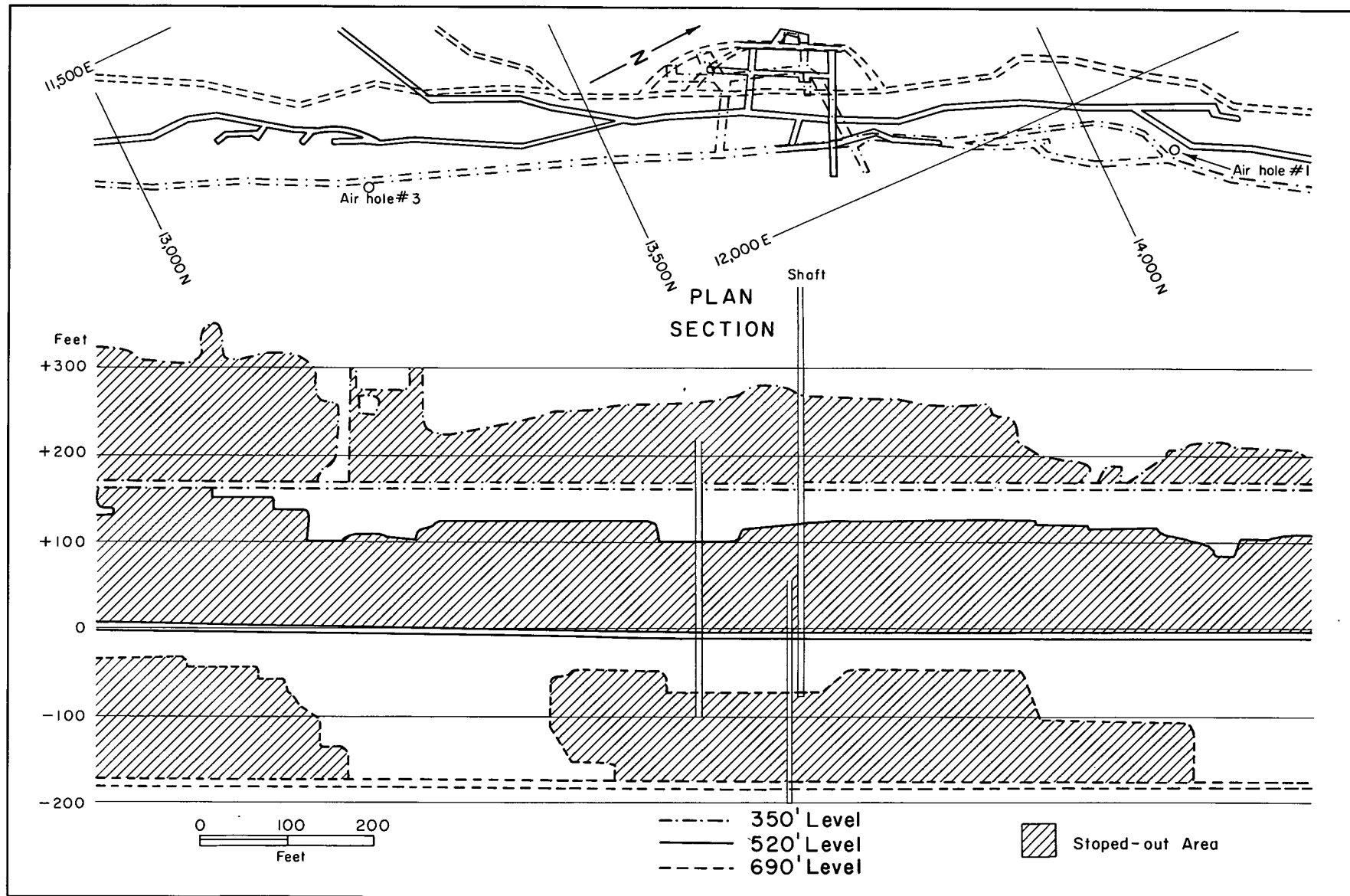
Figure 4. Plan and section of shaft area.
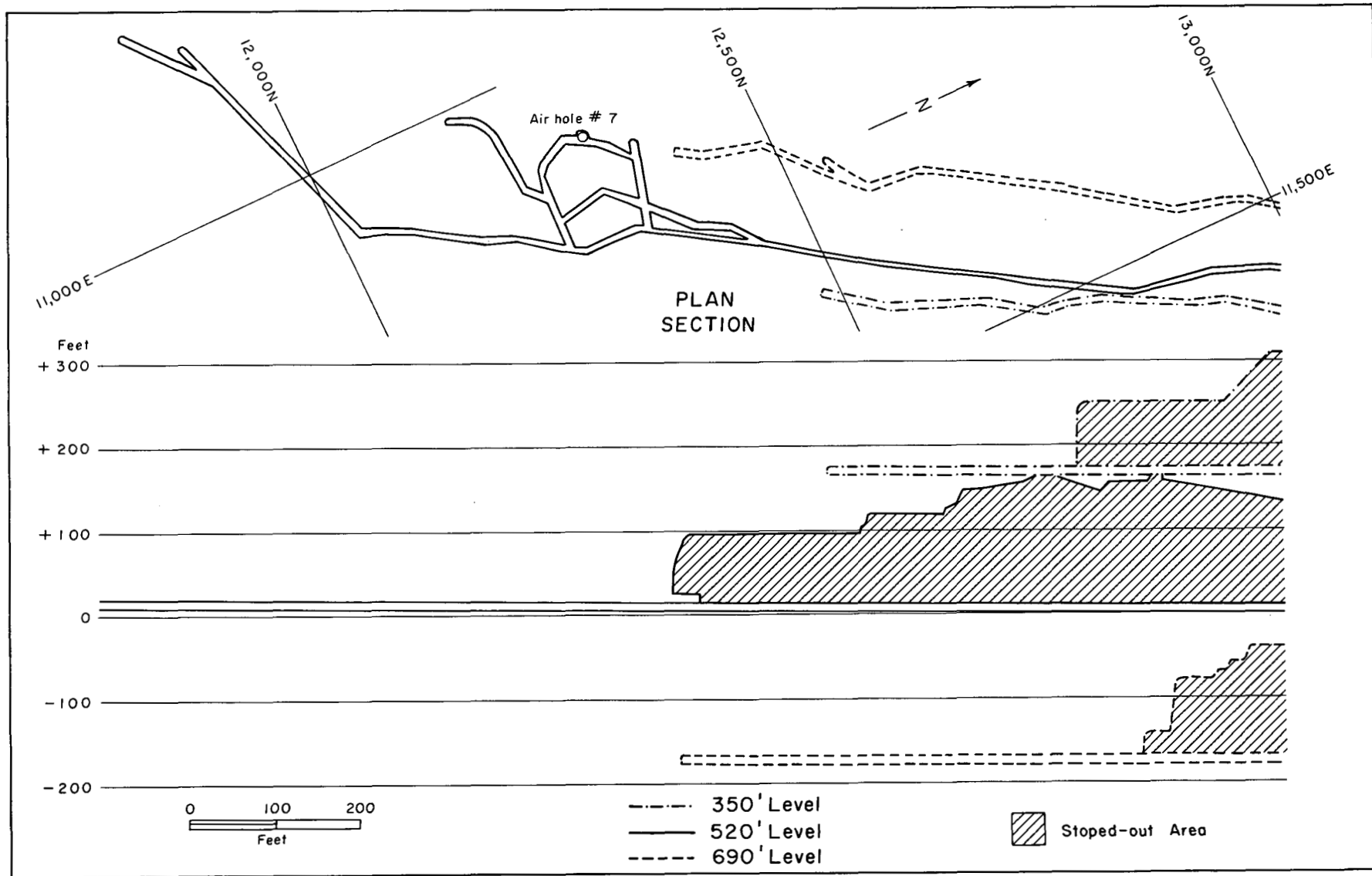
Figure 5. Plan and section of mine southwest of shaft.

PLAN
SECTION

Air hole # 8

10,000E

11,000N

10,500E

11,500N

Feet
+ 300

+ 200

+ 100

0

- 100

- 200

0 100 200
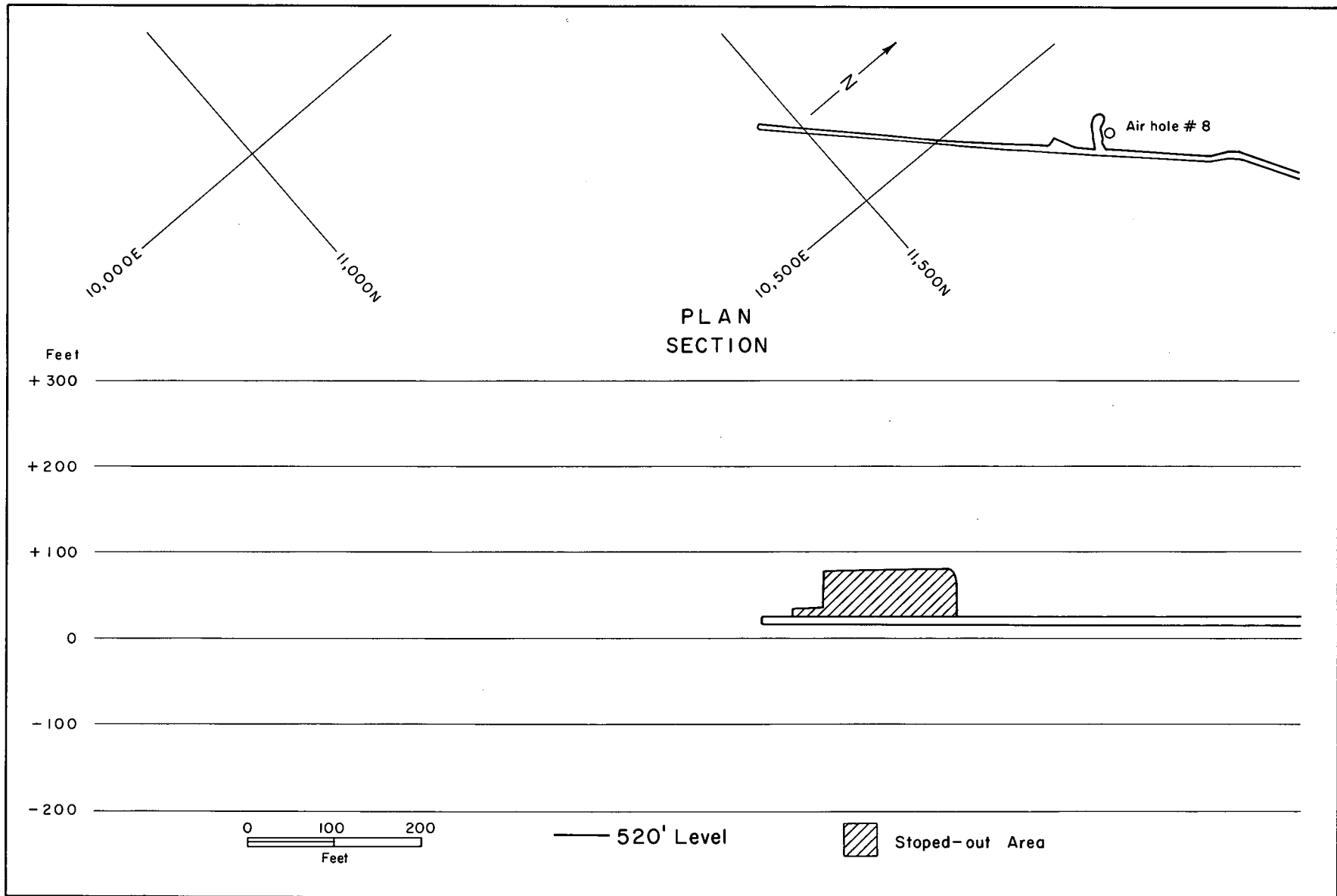Feet

—— 520' Level

Stoped-out Area

Figure 6.   Plan and section of southwest end of mine.

THE EAGLE-BABB-BARNES FLUORSPAR PROJECT, CRITTENDEN COUNTY, KENTUCKY

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ABSTRACT

Core drilling on two properties along the Babb fault system in southwestern Crittenden County, has disclosed a potentially commercial vein-type fluorspar ore body. Drilling data suggest that about 1,000,000 tons of fluorspar ore in indicated and inferred categories exist in the deposit. Preparations are currently under way for developing the ore body.

INTRODUCTION

The announcement by Cerro-FFL Group of plans to construct a new multi-million dollar fluorspar mine and mill in Crittenden County, (Mining Engineering, 1972, p. 19) has once again focused attention on one of the well-known mineral areas in the Western Kentucky fluorspar district.

The project area is located on the Babb fault system about 2 miles north of Salem, Livingston County (Fig. 1). The area of the Babb fault has been known for more than 70 years as a potential mineral region. In 1905, Ulrich and Smith (1905, p. 83, 201-202) recognized a mineralized fault in the area and reported that Eagle Fluorspar Company operated on the Ramon Babb property in 1899 and 1900. This consisted of two shafts and several prospects, the main shaft being 80 feet deep. At one time the Babb area was considered one of the most productive in the district (Hardin, 1955, p. 1).

The area under discussion in this report covers two properties which have long been known in local mining circles as the Eagle-Babb and Barnes tracts. Although there have been several changes over the years in land and mineral rights ownership, the present operators have retained the earlier designations and refer to the project as the "Eagle-Babb-Barnes." It will now be operated as a single property.

[1] FFL Group: Frontier Resources, Five Resources, J. Fred Landers, and F. B. Moodie III.

Prospecting by pits and drilling, and development activity by shallow pits and shaft mining was done on the Eagle-Babb-Barnes by as many as 10 different companies, individuals, and organizations between 1899 and 1967. According to available records from public and private sources, 22 holes were drilled on the Eagle-Babb tract and 25 on the Barnes tract. Three shafts with depths of 200 feet or more were sunk on the two properties. Eagle No. 1 and Eagle No. 2 shafts on the Eagle-Babb were reportedly sunk to depths of 552 feet and 200 feet respectively. The Howard shaft on the Barnes property was reportedly sunk to a depth of 234 feet (Fig. 2). For a summary of the development and exploratory activity between 1899 and 1946, the reader's attention is invited to the discussions by Hardin (1955, p. 33-35) and Swanson and Starnes (1950, p. 10-13).

Hardin (1955, p. 35) wrote that because of the stratigraphy and the character of the fault he believed that fault 2 on the Barnes property offered the best possibility for prospecting. His analysis was prophetic.

GEOLOGIC AND GEOGRAPHIC SETTING

The Eagle-Babb-Barnes project is in the southwestern portion of the Salem 7.5-minute quadrangle which is covered by geologic (Trace, 1962) and topographic maps, both at a scale of 1:24,000. The topography is rolling and of moderate relief, varying from 410 to 540 feet above sea level. In the vicinity of the project area, several sandstone-capped hills and ridges attain elevations of 700
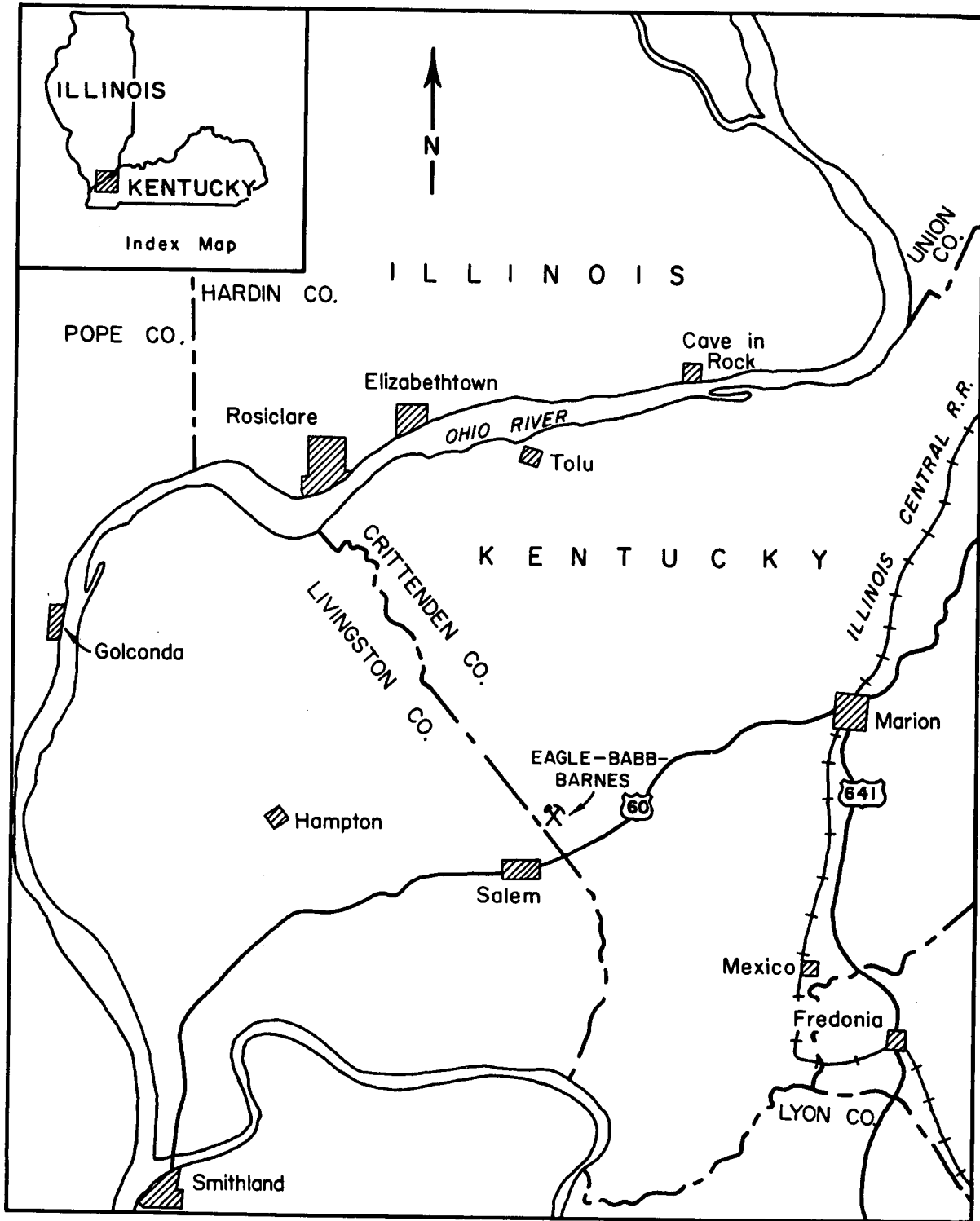
Figure 1. Map of portion of the Illinois-Kentucky fluorspar district showing the location of the Eagle-Babb-Barnes project in Crittenden County, Ky.
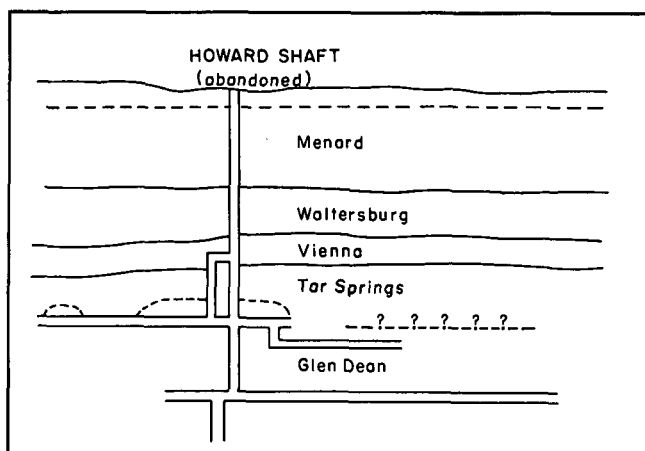
Figure 2. Sketch of the abandoned Howard shaft on the Barnes tract. Data compiled from public and private sources.

to 800 feet. Sandy Creek and its westward- and southwestward-flowing tributaries drain the area.

Rocks of Late Mississippian age occur at the surface; however, few outcrops are present. The Babb fault system extends for more than 2 miles in a northeast-southwest direction across portions of Crittenden and Livingston Counties (Trace, 1962). The footwall block of the Babb system consists mainly of the Ste. Genevieve Limestone. In the northwest, or hanging-wall, block, limestones, sandstones, and shales of Chesterian age are present at the surface. Some portions of the Babb system appear to be represented by a single fault which may be accompanied by a wide brecciated or broken zone. Elsewhere along the trace of the system the displacement may be distributed among several step faults. The maximum displacement, between the Ste. Genevieve Limestone in the footwall and the Menard Limestone in the hanging wall, is approximately 950 feet. Figure 3 is a generalized geologic section of the project area.

The project property is near Kentucky Highway 723, approximately 2 miles north of Salem and U.S. Highway 60. The Illinois Central Railroad passes through Marion, the county seat of Crittenden County, about 12 miles to the east. Cumberland River is 6 miles south of Salem, and the Ohio River is 12 miles to the north and west.

CURRENT PROJECT

In April 1971, F. B. Moodie III recommended to the FFL Group-Cerro Corporation joint venture

that a thorough study be made of all available information on the Eagle-Babb and Barnes properties. This included both published information and records in the hands of the owner.

Study of available data led to the conclusion that the Eagle-Babb property had been drilled but that some of the geologic interpretation might be subject to question. Apparently no thorough exploration program had ever been carried out on the Barnes tract, and the main fault (referred to in some earlier literature as fault 2) had not been tested here. In fact, there had been little drilling along the strike of the Babb fault system on the Barnes property.

The study revealed that the northeast portion of the Barnes property contains two distinct faults, one Cypress against Fredonia, and the other Menard against Cypress. It was this latter fault that was believed to be the main fault, and it was this fault that past drilling had failed to properly explore on this property. Earlier drilling on the Barnes property had apparently followed the Cypress-Fredonia fault.

Evaluation of the information available at this stage in the study led to the conclusion that the Eagle-Babb and Barnes properties contained sufficient fault length under favorable geologic conditions to produce a potentially commercial fluorspar ore body. A short term lease-option was then obtained from the property owner.

Contractural obligations did not allow time for geochemical or geophysical investigations. Because of the scarcity of outcrops and the availability of subsurface and other geological data, new surface geological work was restricted. A drilling program, outlined primarily on the basis of earlier exploratory efforts, commenced July 8, 1971.

The first core hole (Fig. 4), EBB 1, was located to check an earlier drill log which had reported 8 feet of fluorspar ore. Stratigraphic and structural relationships as interpreted from data gathered from the drilling program are shown by a series of geologic cross sections (Figs. 5-9). Dimensions on the cross sections show the ore or mining widths and not the actual vein widths. Veins may contain calcite and other materials which may not be recovered. A shaft, which is now being sunk, and subsequent mining operations will

FORMATION	MEMBER	THICK. (ft)	LITHOLOGY
Menard		± 130	
Waltersburg		2-8	
		18-28	
		8-20	
Vienna		6-12	
		13-21	
Tar Springs		7-10	
		3-10	
		14-75	
		30-90	
Glen Dean		7-16	
		9-12	
		0-30	
		18-40	
		3-6	
Hardinsburg		12-26	
		3-5	
		3-5	
		20-35	
Golconda		4-21	
		6-16	
		20-26	
		2-12	
		5-9	
		2-7	
		20-26	
		2-6	
		2-6	
Cypress		80-100	

Continued

FORMATION	MEMBER	THICK. (ft)	LITHOLOGY
Paint Creek		5-25	
Bethel		75-100	
Renault	Downeys Bluff	25-35	
	Yankeetown	15-30	
	Shelterville	15-30	
Ste. Genevieve	Levias	5-30	
	Rosiclare	10-20	
	Upper Fredonia	25-40	
	Sub-Rosiclare	4-10	
	Lower Fredonia	160-180	
St. Louis		± 400	

Figure 3. Generalized geologic column of the Eagle-Babb-Barnes project area. Adapted from company data.
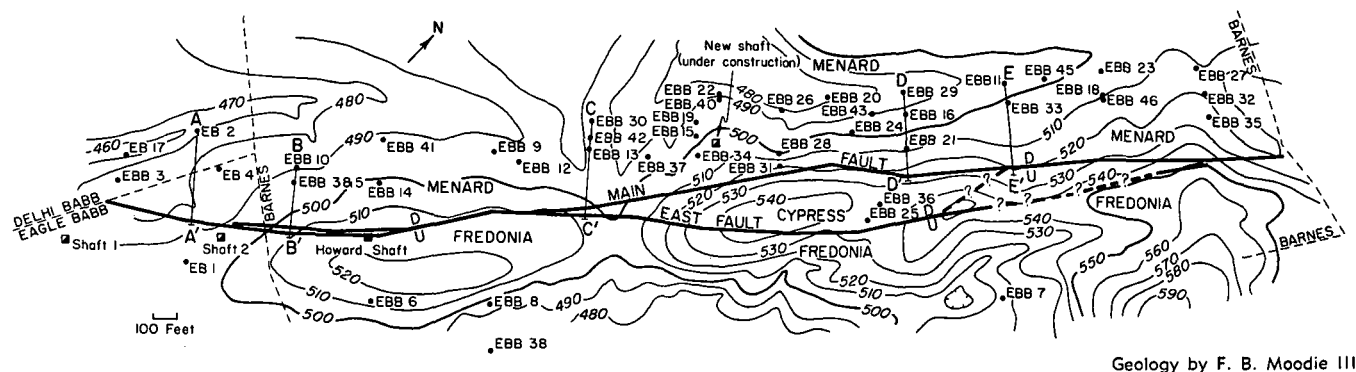
Figure 4. Generalized topographic map of the Eagle-Babb-Barnes area showing location of project core holes.

reveal additional details about the ore body and related geologic controls, which undoubtedly will refine these interpretations.

Core holes EBB 1 and EBB 2 (Fig. 5) on the Eagle-Babb property indicated a sandstone breccia zone outward from the main hanging wall to be approximately 140 feet wide. This zone is highly fractured, faulted, and brecciated. Correlation of these holes with records from earlier drilling was impossible. The only vein that showed any continuity was the vein that lay immediately adjacent to the main hanging wall. It was decided that the hanging wall of the main fault (Menard against Cypress at the surface) was the structure that should be followed across the Barnes property, a distance of more than 5,000 feet.

Core holes EBB 3 and EBB 5 (Fig. 6) immediately across the property line on the Barnes property found the main Babb fault and good mineralization. The faults were better defined. Two veins with a zone of intense brecciation between them were encountered. Here the breccia zone narrowed considerably, being only 10 to 20 feet as contrasted with approximately 140 feet in the first holes.

Since time was of the essence, core hole EBB 7 was located near the north end of the Barnes tract. It was located so that it would cut the east fault (Cypress against Fredonia at the surface) and continue to the main Babb fault. The first fault, Fredonia against Bethel, was encountered at 84 feet (on rods). At 913 feet (rod distance) the hole cut 7 feet (rod distance) of high-grade fluorspar against a hanging wall of Fredonia Limestone. The hole was collared in Fredonia, drilled

more than 1,000 feet at approximately 45 degrees, and bottomed in Fredonia. This was the main fault with a commercial width and grade of ore. This was the first hole on the Barnes tract to intersect this fault at a favorable horizon.

Core hole EBB 9 was located to cut the main Babb fault about halfway between EBB 7 and EBB 3 and EBB 5. This hole encountered 12.2 feet (true width) of high-grade fluorspar (see Tables 1 and 2 and cover photograph). At this point the presence of a potentially commercial fluorspar orebody was suspected. Subsequent drilling further defined the structure and established reserves of ore.

During November and December 1971, four drills operated two 10-hour shifts each to outline the deposit. By January 1972, drill results were encouraging enough to exercise the first phase of the option agreement. Drilling ceased February 1972 with the completion of 45 core holes. The 45 holes, 40 classed exploratory and 5 audit, represented more than 28,000 feet of core taken along the fault strike over a distance of approximately 5,400 feet. All exploratory tests were angle holes, ranging from 45 to 60 degrees. Computed vertical depths ranged from 250 to 800 feet.

Data obtained from the drilling program suggest a fluorspar deposit in the order of 1,000,000 tons in indicated and inferred categories. The vein, a nearly vertical fissure fill, has an average width of 9 feet; height varies from 200 to 400 feet.

Calcite and fluorite were the most abundant minerals encountered in the drilling program. The fluorite was predominantly white to brown (see cover photograph). The average sphalerite con-
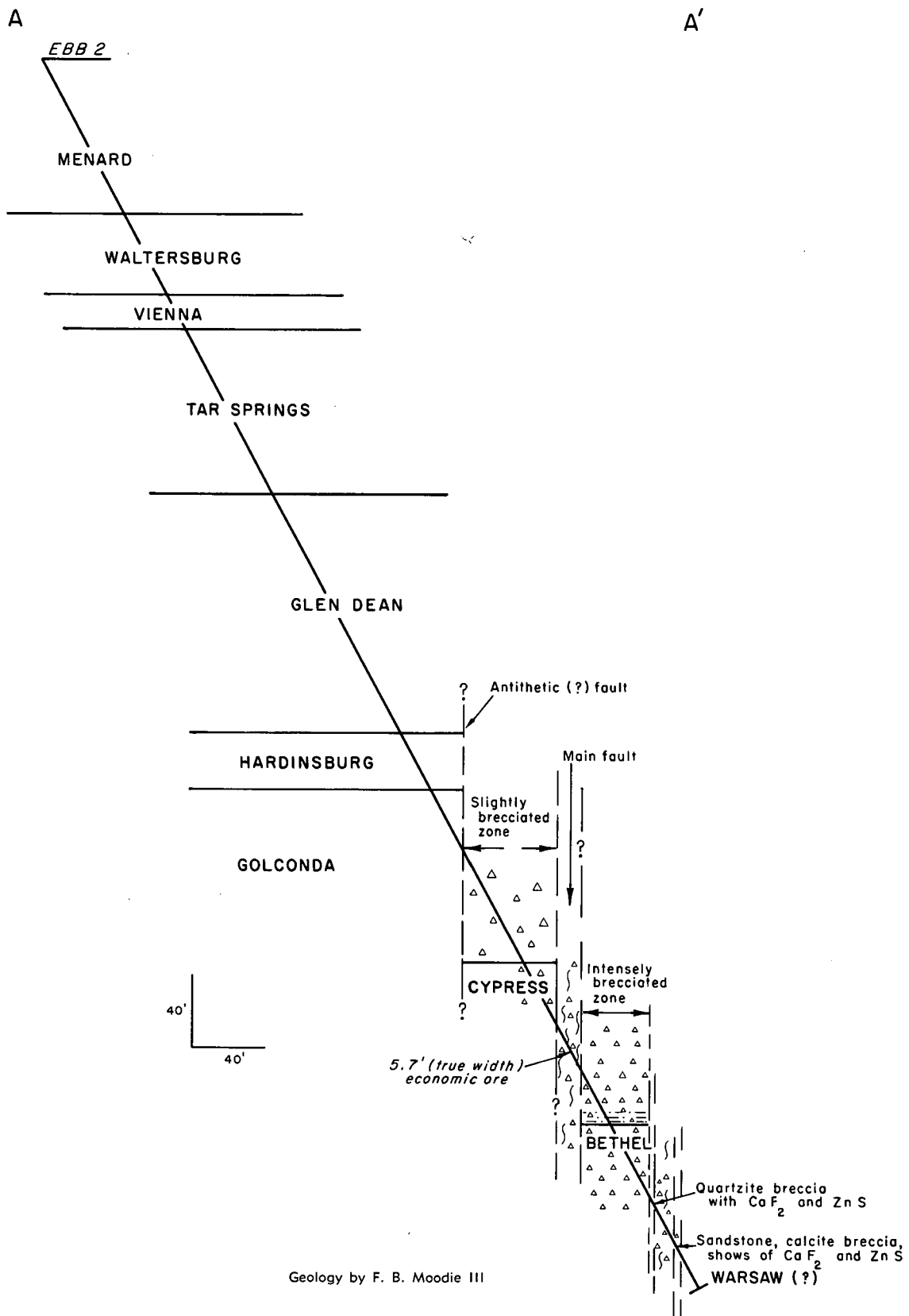
Figure 5. Cross section A-A'. An unusually wide zone of highly fractured, faulted, and brecciated sandstone was encountered in core hole EBB 2.
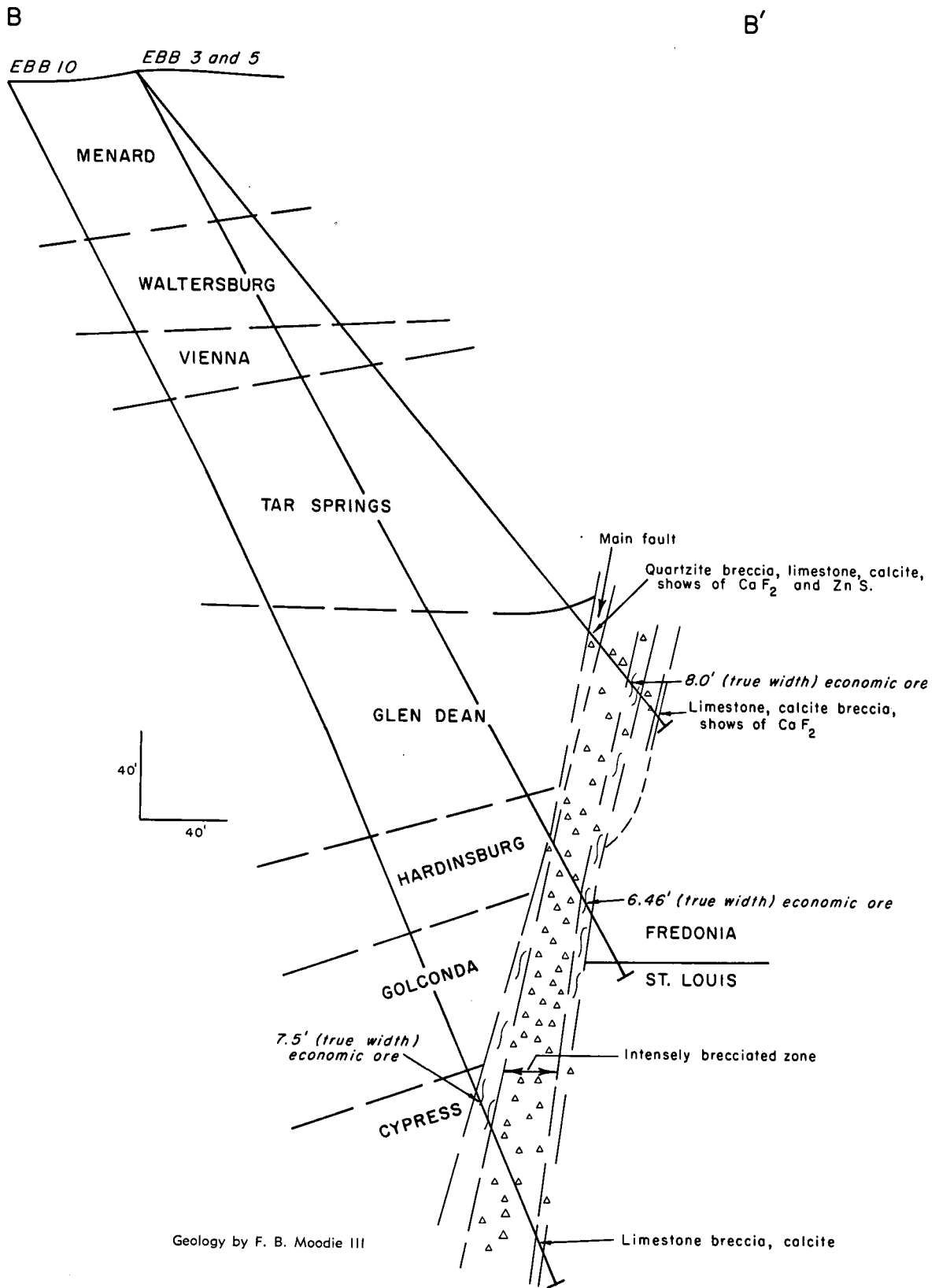
B   B′

EBB 10   EBB 3 and 5

MENARD

WALTERSBURG

VIENNA

TAR SPRINGS

· Main fault

Quartzite breccia, limestone, calcite,
shows of Ca F_2 and Zn S.

8.0′ (true width) economic ore

GLEN DEAN

Limestone, calcite breccia,
shows of Ca F_2

40′

40′

6.46′ (true width) economic ore

HARDINSBURG

FREDONIA

GOLCONDA

ST. LOUIS

7.5′ (true width)
economic ore

Intensely brecciated zone

CYPRESS

Geology by F. B. Moodie III

Limestone breccia, calcite

Figure 6. Cross section B-B′. The faults were better defined and the brecciated zone thinner than in core hole EBB 2. Good mineralization occurs along the main fault.

TABLE 1.—LOG OF PORTION OF CORE EBB 9. HOLE WAS COLLARED AT 65 DEGREES. ALL DEPTHS AND INTERVALS ARE DISTANCES ON RODS. GEOLOGY BY F. B. MOODIE III

Depth (in feet)		Distance drilled (in feet)	Core recovered (in feet)	Analysis Number	Description
From	To				
549.5	552.2	2.7	2.7	9-A1	Quartzite breccia (Cypress Ss.) with sphalerite and fluorspar.
552.2	557.0	4.8	4.8	9-A2	Limestone breccia (Fredonia (?)) with black gouge, sphalerite and fluorspar. This appears to be in the vein.
557.0	559.0	2.0	2.0	9-A3	Fluorspar, dark-blue, with gouge and limestone breccia with sphalerite.
559.0	564.0	5.0	5.0	9-A4	Fluorspar, hard, crystalline, amber to brown, with sphalerite.
564.0	569.0	5.0	5.0	9-A5	Same
569.0	574.0	5.0	5.0	9-A6	Same
574.0	581.4	7.4	7.4	9-A7	Same
581.4	586.2	4.8	4.8	9-A8	Fluorspar, crystalline, dark-blue, and limestone breccia. Fault slip at 584.6.
586.2	591.2	5.0	5.0	9-A9	Calcite, petroliferous, with scattered shows of brown fluorite.
591.2	596.2	5.0	5.0	9-A10	Same; brown fluorite at 592.2 and 592.7.
596.2	603.0	6.8	6.8	9-A11	Same; brown fluorite at 597.3 and 598.6. Purple fluorite veinlet with pale yellow sphalerite at footwall contact 603.0.

TABLE 2.—ANALYSIS OF PORTION OF CORE EBB 9. VALUES OF CONSTITUENTS IN PERCENT. SEE TABLE 1 FOR DESCRIPTION OF SAMPLES

Sample No.	CaF_2	SiO_2	$CaCO_3$	ZnS	R_2O_3
9-A1	18.22	58.28	6.12	6.92	—
9-A2	20.48	17.62	50.88	4.78	—
9-A3	52.08	13.94	16.12	8.43	—
9-A4	96.79	0.32	0.43	1.19	0.42 PbS
9-A5	94.14	0.43	0.77	2.57	0.51 "
9-A6	95.38	0.77	1.59	1.32	0.47 "
9-A7	93.58	0.81	1.13	1.63	1.13 "
9-A8	57.82	22.16	14.98	0.89	0.56 "
9-A9	3.16	5.42	90.62	0.44	—
9-A10	2.94	1.22	95.38	—	0.46 PbS
9-A11	7.22	2.32	89.92	—	0.54 "

tent of the deposit is less than 2 percent, and the average galena content less than 0.5 percent. Some pyrite is present but no barite has been noted.

The main ore starts from the top of the Cypress Sandstone and extends down into the lower section of Chesterian rocks. However, a few holes indicate that at some places along the strike, ore shoots may extend upward as high as the Tar Springs Sandstone, all on the hanging-wall side.

The footwall of the fault apparently had little effect on mineral accumulation.

The principal continuity along the Babb fault system in the Eagle-Babb-Barnes project area is the hanging-wall (Menard) side rather than the footwall (Fredonia) side.

As indicated earlier, intense brecciation is present in portions of the Babb fault system. The rocks in the hanging wall, particularly the limestones and more highly indurated sandstones, have been highly fractured. The rocks in the footwall have been much less disturbed. Mineral accumulation may be related, in part, to the broken-rock conditions in the hanging wall.

It has long been accepted that lithologic characteristics had marked effect on localizations of veins in the district. The largest fluorspar deposits have been associated with the purer limestones of the Ste. Genevieve and Renault formations. Since these formations have not been thoroughly tested on the hanging wall of the principal Babb structure in the Eagle-Babb-Barnes project area, it is possible that a substantial reserve of ore is present in deeper zones. Further exploration will be necessary to determine the total depth of fluorspar ore bodies in the Babb fault system.
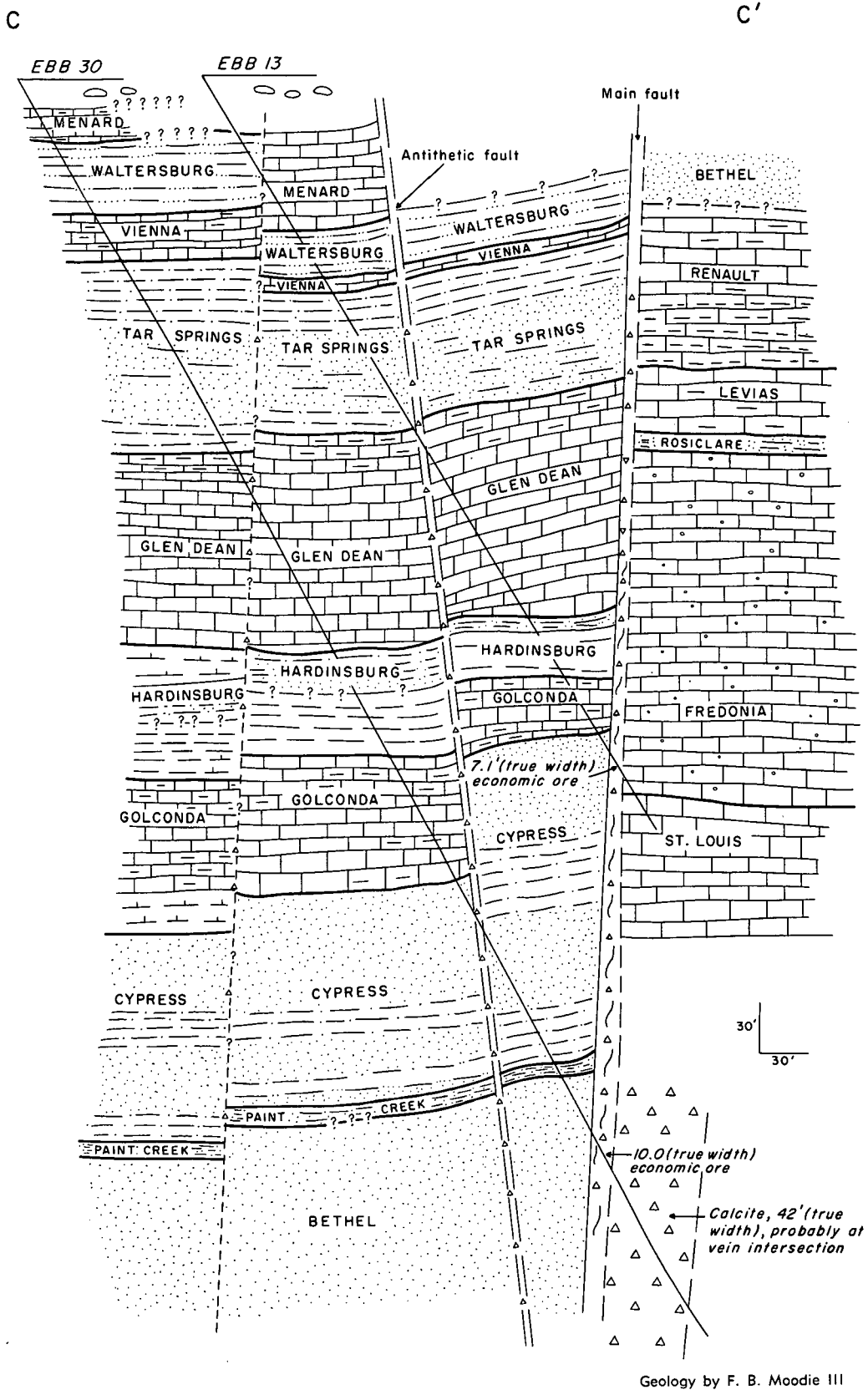
Geology by F. B. Moodie III

Figure 7. Cross section C-C'. Good mineralization continues along the main fault. Differences in thickness of the Cypress formation may be due to unrecognized faults or other structural conditions.
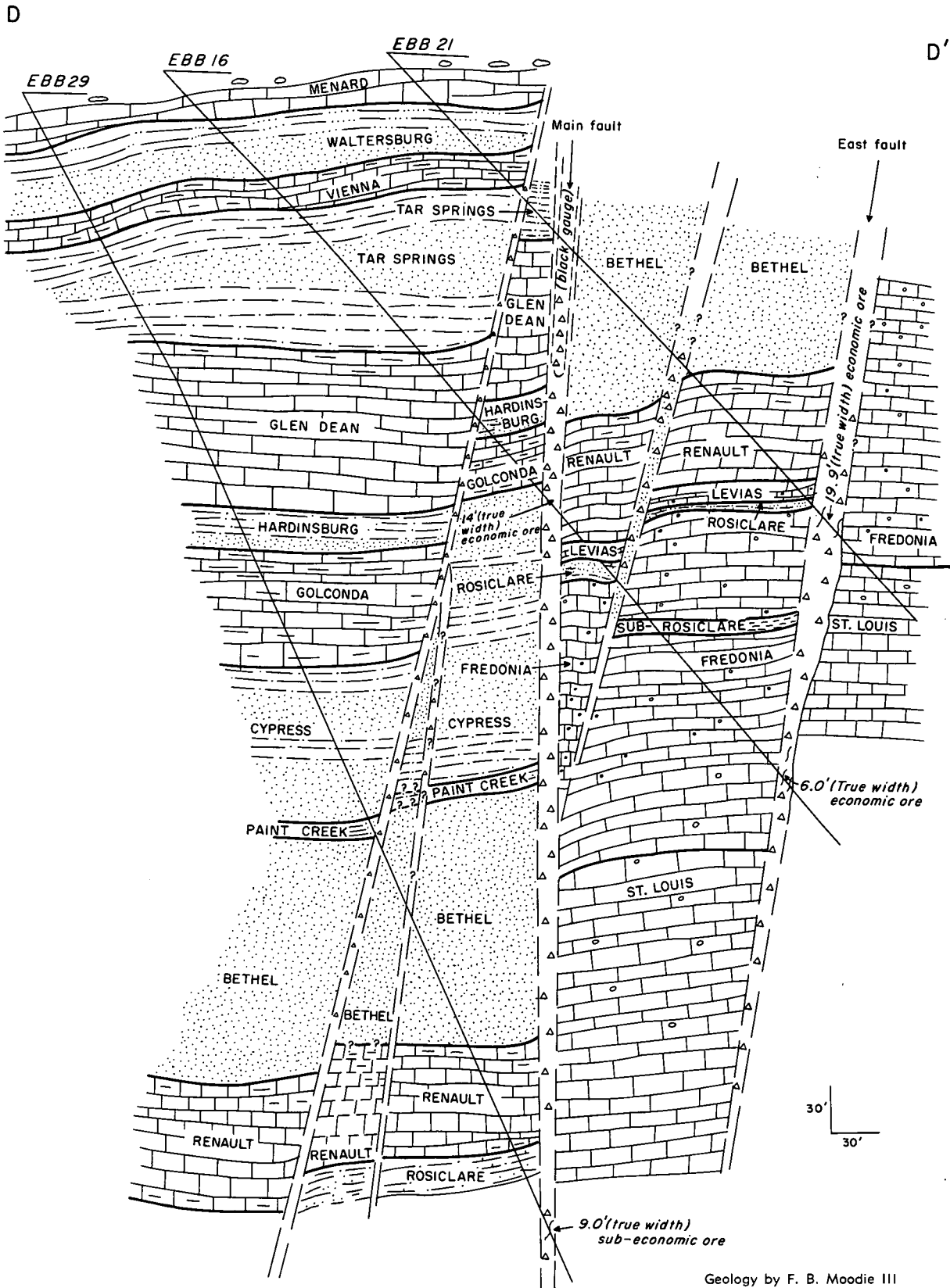
Figure 8. Cross section D-D'. Fluorspar ore of commercial grade and width was encountered in both the main fault and the east fault. As in cross section C-C', differences in thickness of the Cypress formation may be due to unrecognized faults or other structural conditions.
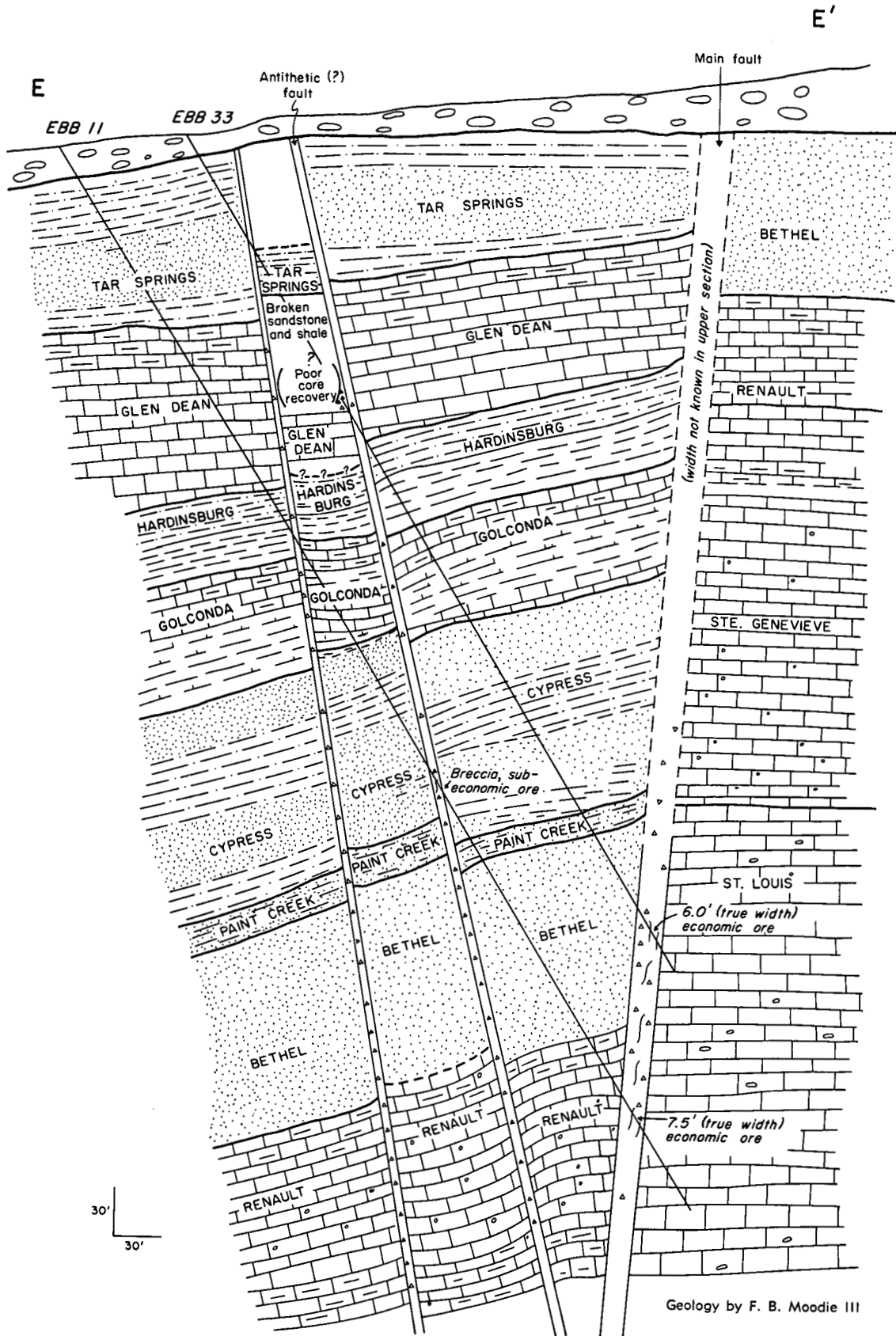
Figure 9. Cross section E-E'. Commercial grade and width fluorspar ore extended along the strike of the main fault to the north end of the Barnes property, a distance of some 5,000 feet.

Hardin (1955, p. 24-25) observed that vein widths increase in the steeper segments of the Babb fault system. Drilling on the Eagle-Babb-Barnes properties indicate that the faults were steeper where they crossed the massive limestone formations, which coincide with principal zones of mineral occurrence.

Differences of indicated thickness of the Cypress formation in Figures 7 and 8 may be due to distortion, dip of beds, unrecognized faults, or other deformation.

Fault gouge, derived primarily from shales of Chesterian age, is commonly present in the fault system. It is thought that this material served as a trap for migrating mineral solutions. Earlier exploratory drilling apparently intersected the fault zone above or through the gouge material, whereas the current program was designed to test zones beneath gouge accumulations. Thirty-two of the exploratory holes encountered commercial-grade ore.

Holes collared in the Fredonia Limestone commonly encountered cavernous conditions for the first 200 feet (on rods at 45 degrees), resulting in poor core recovery.

CONCLUSIONS

Core drilling on the Eagle-Babb-Barnes prospect has demonstrated that the Western Kentucky fluorspar district is still capable of yielding commercial-size bodies of fluorspar ore. Undoubtedly others will be disclosed in the future.

The 1:24,000-scale areal geologic maps produced by the Kentucky Geological Survey-United States Geological Survey cooperative mapping program are providing an additional tool to use in prospecting programs. These 7.5-minute quadrangle maps, which are now completed or will be completed in the near future for the district, are giving earlier geological work an added dimension. However, core drilling is the only way to determine the presence, size, and shape of an ore body.

The long-accepted stratigraphic and structural considerations are still valid. However, it appears that many deeper formations have not been adequately tested. Future drilling programs should be designed to thoroughly test the deeper units in potentially favorable areas. This will mean an increase in exploration costs, but the results should be more rewarding.

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