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Research Proposal Submitted to the National Science Foundation
by

Boston University
725 Commonwealth Avenue
Boston, Massachusetts 02215

Title: Petrological and Geochemical Studies of the Stratiform Fluorite-Barite-Sulfide Deposits, Cave-In-Rock District, Illinois

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ABSTRACT

It is proposed to study the processes of the formation of the stratiform lead-zinc-fluorite-barite deposits in the Mississippian limestones in the Cave-In-Rock district, southern Illinois, in particular, to study the interrelationships between diagenesis and epigenesis including ore genesis. Little is known about the factors, contributed by the physical, chemical, mineralogical and paleohydrological characteristics of the host limestones, in localizing large stratified ore deposits. Previous work by the author and his co-workers has revealed that there exist complicated interrelationships between lithogenesis and ore genesis and that ore minerals in ancient limestones tend to follow a characteristic sequence of precipitation. The reasons for such a sequence are, however, not well understood. Modern approaches of sedimentology and petrology have not as yet been applied to the host carbonate rocks in this region. It is anticipated that a detailed study of both sedimentology and ore petrology near and within the ore bodies can provide very valuable information on the ore genesis of the Mississippi Valley type deposits.

The work proposed will involve: 1) Field investigation in order to carefully study and record important features found in Minerva No. 1 Mine and to systematically collect samples for laboratory study; 2) Petrological investigations of the host carbonate and ore-bearing rocks and to some extent the overlying sandstone and shale units in order to find important sedimentological and geochemical factors of the host rock which are responsible for localizing the ores; 3) Analysis of strontium content in fluorites in order to understand geochemical inter-reaction between the host rocks and the migrating ore fluids; 4) Determination of strontium/calcium ratios in barites from the Minerva No. 1 ore body in order to investigate zoning and temperature gradients, if any, and paleohydrochemical role in barite depositions and dissolution; and 5) Evaluation of above information within the context of field studies, sedimentology, present knowledge of carbonate petrology and pertinent experimental and theoretical data on fluorite and barite solubilities.

The results of these investigations will hopefully shed a new light on the origin of the Cave-In-Rock deposits and other numerous ore deposits of the Mississippi Valley type.

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Broad Objectives and Expected Significance

Ore deposits to be investigated are normally regarded as a sub-group of the widely distributed economically important stratiform lead-zinc-barite-fluorite deposits (Mississippi Valley Type). These deposits are characterized by low temperature mineral associations such as galena, sphalerite, barite and fluorite, confined more or less concordantly to certain carbonate formations.

During the last 100 years, the origin of this type of ore has been the subject of heated controversies. Many of the details of the available genetic theories lack support from field and laboratory data. As recently as 1967, OHLE (Economic Geology, Monograph 3, p. 38) stated "After 100 years of study it is still a great source of wonder as to just what rock property or combination of properties contributed to the development of such diverse ore types in such close proximity". This stresses the importance of the lithogenesis of the host carbonate rocks in determining the origin of these ore deposits.

The present proposal involves a detailed study of the sedimentology of the host carbonate rocks and their effect on the mineralization. SNYDER (1967, p. 6) recognized the importance of sedimentary petrology of the host rocks by stating that "Diagenesis may well play an important role in mineralization. Certainly it appears to be a fruitful field for research on deposition of ore sulfides of either diagenetic or epigenetic origin".

The author's previous work on the geochemistry and the diagenesis in carbonate rocks as well as his research on sulfide deposits will be a valuable aid in investigating the syngenetic, diagenetic and epigenetic features of the host rocks and ores, and determining the paragenetic sequence of deposition. The results of the proposed investigation will hopefully lead to a better understanding of the nature of the interaction between the carbonate host rocks and the ore solutions.

General Geological Setting

Introduction

The Cave-In-Rock district of southern Illinois is located in the northern part of the larger southern Illinois-Kentucky fluorite barite mineral district. The latter lies on the extreme southern portion of the Illinois Basin and on the northern portion of the Mississippi River Embayment, surrounded by three erosional or tectonic highs of Precambrian Basement rocks visible in surface exposures and shallow drill holes. These highs are the Ozark Dome to the west, the Cincinnati Arch and the Nashville Dome to the east.

The buried Precambrian surface undulates mildly with southwest regional slope and descends deeply beneath the Illinois Basin and Mississippi River Embayment, into which thick sedimentary rocks from Late Cambrian to Late Pennsylvanian age are filled (HEYL et al., 1965; WHEELER, 1966). The geology of the southern Illinois district can best be described as an area of relatively undisturbed nearly flat-lying sedimentary rocks, except for the numerous normal faults and a domal structure (EARDLEY, 1962).

The sedimentary strata in the Cave-In-Rock district of southern Illinois dip gently northward into the Illinois Basin and are cut and disturbed by the ENE trending Shawneetown-Rough Creek Fault Zone which occurs a few miles north of the mining district. The Fault Zone consists largely of two dropped-down segments which are divided by three southwest-northeast trending fault systems. They are from the south: The Peters Creek Fault System, the Hogthief Creek Fault System and the Goose Creek Fault System. This Fault Zone is about 4 km wide with a structural relief of about 300 to 400 m (S. WELLER et al., 1920; M.J. WELLER et al., 1952; BAXTER et al., 1963; BAXTER and DESBOROUGH, 1965; HEYL et al., 1965; BAXTER et al., 1967).

About 15 km north of the town Rosiclare, the Helderberg Limestone of Lower Devonian age is exposed at the central high of the Hicks Dome which is an oval swell or uplift of strata with a diameter of about 15 km. The central core of the Dome is ringed by rocks of the Mississippian and Pennsylvanian age. The concentric outcrop pattern is obscured on the southern side of the Dome by the younger east-west trending Rock Creek Graben Fault System.

Within the periphery of the Dome, dike-like intrusive masses consisting of fragments of feldspar, quartz and granite in a matrix of rock flour have

been reported (WELLER, GROGAN and TIPPLE, 1952; BROWN, EMERY and MEYER, 1954). Highly altered north-west striking peridotite and lamprophyre dikes were also mapped in the district (WELLER and GROGAN, 1945).

Following the igneous dike formation, the northeast trending faults of Rock Creek graben developed (SNYDER and GERDEMANN, 1965). The vein type of fluorite-sulfide mineralization found in the southwestern part of the district are mainly associated with this fault system. The genetic relationships between Hicks Dome, the igneous activity, the faults and the fluorite mineralization near Rosiclare are not clear.

The mines to be investigated in this proposal are located about 18 km ESE of the Hicks Dome. One of the major fault systems of the district, namely the Peters Creek Fault lies approximately 5 km north of the mines. The hanging wall of the Peters Creek Fault has been dropped down about 300 m in this area. The most frequent strike of the faults is N 50° - 60° E; however, faults striking from N25°W - N 70° W occur in some of the mines in the district.

The Illinois Fluorite-Barite-Lead-Zinc Deposits

Previous Work

The geology and ore deposits of the southern Illinois district have been studied over a long period of time. The following is a list of more than 90 publications subdivided according to the main topic, and arranged chronologically within each subdivision.

District geology and structures: S. WELLER et al., 1920; S. WELLER, 1927; CURRIER, 1935; CURRIER and WAGNER, 1944; WELLER and GROGAN, 1945; WELLER, GROGAN and TIPPIE, 1952; BROWN, EMERY and MEYER, 1954; STONEHOUSE and WILSON, 1955; CLEGG and BRADBURY, 1956; HEYL and BROCK, 1961; BAXTER, POTTER and DOYLE, 1963; ROSS, 1963; MCGINNIS and BRADBURY, 1964; HEYL, BROCK, JOLLY and WELLS, 1965; BAXTER and DESBOROUGH, 1965; BAXTER et al., 1967.

Economic geology: S.F. EMMONS, 1893; BAIN, 1904 and 1905; SPURR, 1926; SCHWERN, 1928; BASTIN, 1931; LINDGREN, 1933; CURRIER, 1937; BASTIN, 1942; BISHOP, 1947; MUIR, 1947; BISHOP and NEEDHAM, 1949; NAKOWSKI, 1949; GROGAN, 1949; BASTIN, 1950; EMERY, 1950; CRONK, 1951; NAKOWSKI, 1952; WELLER, GROGAN and TIPPIE, 1952; NAKOWSKI, 1958; OESTERLING, 1959; BRADBURY, 1959; TRACE, 1960; FINGER, RISSER and BRADBURY, 1960; HEYL and BROCK, 1961; PARK, 1962; BRECKE, 1962, 1964 a and b, 1965 and 1967; AMSTUTZ et al., 1964; ERICKSON, 1965; PINCKNEY, 1966; AMSTUTZ and PARK, 1967; PARK, 1967; GROGAN and BRADBURY, 1967 and 1968;

PARK, 1968; BROWN, 1970; HEYL, 1970; PARK, 1971.

Paleogeography and sedimentology: SUTTON and WELLER, 1932; TIPPIE, 1944 and 1945; SWANN and ATHERTON, 1948; POTTER and SIEVER, 1956; WELLER, 1957; POTTER and GLASS, 1958; POTTER and PRYOR, 1961; SWANN and WILLMAN, 1961; PARK, 1962; POTTER, 1962 a and b; POTTER and PETTIJOHN, 1963; LINEBACK, 1970; BRISTOL and HOWARD, 1972.

Petrology: GRAF and LAMAR, 1950; SIEVER and POTTER, 1956; PARK, 1962; BRADBURY, 1962; AMSTUTZ and PARK, 1967; LACEY and CAROZZI, 1967; PARK, 1968; PARK and SCHOT, 1968 a and b; CAROZZI and ROCHE, 1968; CHOQUETTE, 1971.

Liquid inclusion studies: GROGAN and SHRODE, 1952; FREAS, 1961; CZAMANSKE, ROEDDER and BURNS, 1963; HALL and FRIEDMAN, 1963; ROEDDER, 1965 and 1967; PINCKNEY and HAFFTY, 1970.

Isotope studies: HEYL, DELEVAUX, ZARTMAN and BROCK, 1966; PINCKNEY and RYE, 1972.

Experimental replacement studies: AMES, 1961 a and b; BAXTER, 1963.

Geochemical mass transfer studies: PINCKNEY and HAFFTY, 1970; PARK, 1971; PLUMMER, 1971.

Classification of Ore Deposits

The mineral deposits of the entire district may be classified according to the occurrence and mode of deposition into three types: stratiform deposits, vein deposits and residual deposits (BASTIN, 1931 and WELLER et al., 1952).

The stratiform type, part of which is to be studied in the present proposal, is located in the northeastern part of Hardin County, Illinois, commonly referred to as the Cave-In-Rock fluorspar district. This type is commonly accepted by economic geologists as "Mississippi Valley Type" (BROWN, ed., 1967). The size of the ore bodies is variable; it is rarely more than 5 km long, 10-300 m in width, and up to 10 m thick. On a large scale, it is considered to be congruent in relation to the host carbonate rocks. The principal economic mineral is fluorite. Sphalerite, galena, and barite occur in varying amounts in the district.

The vein type includes much of the past economic deposits in the district. The fluorspar bearing veins of the Rosiclare area occur along the faults,

following the wide range of stratigraphic column from Middle Devonian to Lower Pennsylvanian. However, the most productive veins are along one or both walls of Ste. Genevieve Limestone and St. Louis Limestone Formations of upper Valmeyeran Series of Mississippian Period. The thickness of the veins varies from a mere film to more than 10 m. The principal minerals are fluorite and calcite; other minerals in small amounts are quartz, galena, sphalerite, pyrite, chalcopyrite, barite, gypsum and bitumen (BASTIN, 1931 and WELLER, GROGAN and PIPPIE, 1952).

The residual deposits which occur along the outcrops of the vein deposits are economically insignificant, although they were mined earlier.

The vein type deposits are believed to have originated essentially through simple migration of ore solutions along fault planes and consequent deposition of ore minerals along them. Along some veins, however, thin replacement zones more or less parallel to the veins are reported to occur (WELLER et al., 1952).

Most of the workers consider the stratiform type deposits as of epithermal replacement origin. Acidic solutions which contained a high amount of F are believed to have ascended along fault and fracture zone(s), spread laterally and replaced limestone host rocks rhythmically below impervious shale or sandstone beds. As for the exact mechanism of replacement, various theories have been suggested. However, an epigenetic, metasomatic rhythmic replacement origin (periodically fluctuating threshold of ore solutions and consequent changes in their composition) has generally been favoured among the previous workers (BASTIN, 1931; GROGAN, 1949; WELLER et al., 1952; BRECKE, 1962; GROGAN and BRADBURY, 1968).

As for the source of the ore constituents, deep igneous (GROGAN, 1949; BRECKE, 1962; in part, HALL and FRIEDMAN, 1963), brine (in part, HALL and FRIEDMAN, 1963; HEYL et al., 1965; PINCKNEY, 1966; in part, PARK, 1968) and marine sedimentary sources (in part, PARK, 1968) have been postulated.

The time of mineralization has been postulated to be Cretaceous (HALL and FRIEDMAN, 1963; BRECKE, 1964 b).

Stratigraphic Control of the Stratiform Deposits

The sedimentary rocks exposed in the southern Illinois mining district range from Devonian through Pennsylvanian. Detailed account on the stratigraphy of the district is dealt with by WELLER et al (1952), SWANN and WILLMAN (1961), BAXTER et al. (1963, 1965 and 1967).

The bedding-replacement stratiform deposits occur from a few meters below the base of the Spar Mountain Sandstone Member of the Upper Valmeyeran Series to the base of the Bethel Sandstone Formation of the Lower Chesterian Series. The three main ore-bearing limestone horizons, from oldest to youngest are: the upper parts of the Fredonia Member, the Joppa Member of Ste. Genevieve Formation, and the upper part of the Downeys Bluff Formation. All three horizons are within carbonate sequences and are overlain by calcereous sandstones and locally by thin shale units (Fig. 1). Small ore bodies also occur in the Karnak and Levias Limestone Members.

The following is a list of the major mines along each of the above three major ore-bearing horizons:

The upper part of the Fredonia Limestone Member: W.L. Davis-Deardorff Mine, SSW portion of Hill Mine, Cave-In-Rock Mine, and Lead Hill Mine.

The upper part of the Joppa Limestone Member: Hill Mine, West Green, Crystal Mine, Victory Mine, and Spar Mountain Mine.

The upper part of the Downeys Bluff Limestone Member: Minerva No. 1 Mine, Oxford Mine, North and East Green Mines, W.L. Davis-A.L. Davis Mine.

The author has studied in detail the ore bodies in the W.L. Davis-Deardorff Mine (Fredonia horizon), the Hill Mine (Joppa horizon) and the Oxford Mine (Downeys Bluff horizon) (PARK, 1967; PARK and SCHOT, 1968; PARK and AMSTUTZ, 1968; AMSTUTZ et al., 1964; AMSTUTZ and PARK, 1967 and 1971; PARK, 1971). He has visited several of the others listed above, as well as several of the vein deposits in the Rosiclare area. A brief description of each of 3 producing horizons follows.

1. Upper part of Fredonia Limestone Member

The base of the overlying Spar Mountain Sandstone, where it occurs, is usually about 20 m below the base of the Rosiclare Sandstone Member. The Spar Mountain Sandstone Member occurs southeastwards from the south-eastern part of the Deardorff Mine. In this area the Spar Mountain thickens from 0 to 3 m within several meters of horizontal distance. Here soft green shale occurs at the base. The sandstone is variably calcareous, the calcareous part being bituminous micrite. It shows sometimes incipient nodular bedding. The marginal distribution of the Spar Mountain Member in the periphery of the

System	Series	Mega group	Group	Formation	Member	Lithology and approx. thickness		
MISSISSIPPIAN	Chesterian	Pope	Golconda	Haney		limestone; 10 m		
				Fraileys		shale; 25 m		
				Beech Creek		limestone; 2 m		
			West Baden	Cypress		sandstone; 25 m		
				Ridenhower		sandstone; 15 m		
				Bethel		sandstone; 25 m		
			Valmeyeran	Mammoth Cave	Cedar Bluff	Downeys Bluff		limestone; 9 m
						Yankeetown		shale; 7 m
						Renault	Shetlerville	limestone; 7 m
		Levias			limestone; 7 m			
	Ste. Genevieve	Aux Vases			Rosiclare	sandstone; 7-10 m		
					Joppa	limestone; 9 m		
					Karnak	limestone; 9 m		
					Spar Mountain	sandstone; 0-2 m		
					Fredonia	limestone; 25 m		
		St. Louis		limestone; 130 m				

Fig. 1. A condensed stratigraphic section, Cave-In-Rock fluorite district, southern Illinois. The three stippled portions represent the stratigraphic horizons of the ore layers. Stratigraphic section after BAXTER, et al. (1963).

Deardorff Mine strikes roughly N 60° E (BRECKE, 1962), which is roughly parallel to general strike of ore bodies in the district.

Where the Spar Mountain Sandstone Member does not occur, it becomes difficult to recognize the boundary between the Fredonia and the overlying Karnak Member. In the Deardorff Mine, where the Spar Mountain is absent, the base of the Karnak is usually recognized by dark mm-sized lenticular intra-formational micrite breccias embedded in dark brown, massive, fine-grained dolomitic limestone, or by a thin shale layer. The lithologic characteristics of the Spar Mountain and Karnak Member indicate that they have been deposited in quiet marine conditions.

The Fredonia Member along the ore horizon consists dominantly of bio-calcarenitic to oolitic limestone. The lithology of the Fredonia Member, however, in the Deardorff Mine is variable in detail. Within 50 cm from the base of ore layers, it is usually dark, siliceous, dolomitic and recrystallized.

In the Hill Mine, the Spar Mountain Sandstone is erratically distributed with its thickness varying between 0-1 m.

The absence of the Spar Mountain Sandstone Member in places is thought to be a result of subaqueous erosion.

2. Upper part of Joppa Limestone Member

The Rosiclare Sandstone Member which overlies the Joppa Member consists mainly of 7 to 9 m of grey to green, well-sorted, fine-grained sandstone. The upper part of the Rosiclare is grey in color and is transitional upward through a sandy oolitic limestone of the Levias Limestone Member. The lower part of the Member is usually green and calcareous with or without shaly or silty zone.

The Joppa Limestone Member is divided into three units in the field by BRECKE (1962). In upper 3 m it is usually light grey to buff oolitic to bio-arenitic limestone with minor amounts of micritic facies. The latter may contain varying amounts of green shale. The oolitic limestone may contain in places bitumen between cement calcites. In the Hill Mine, the uppermost 7 m of the Joppa frequently contain broken pieces of shale which otherwise overlies stratigraphically the Joppa. This indicates, along with a sporadic occurrence of the shale unit, that agitation, local emergence, erosion by waves and redeposition of the lowermost Rosiclare shale unit have been active during the late Joppa and early Rosiclare time. Figure 2 is a detailed stratigraphic section found on a mine wall, 30 m northwest of the Hill mine shaft.

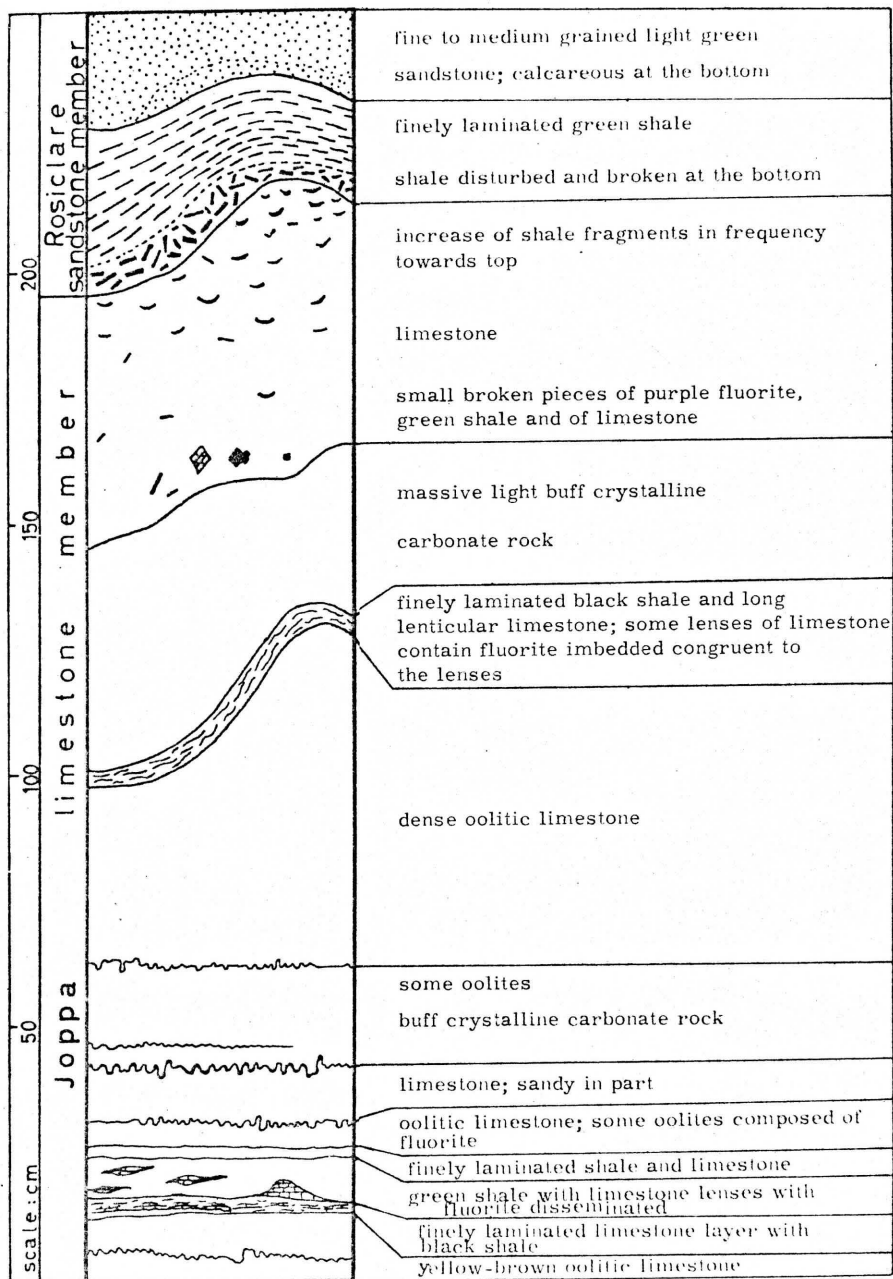


Fig. 2. Detailed stratigraphic section of the uppermost part of the Joppa Member and the lowermost part of the Rosiclare Member, found on a mine wall, 30 m northwest of the Hill Mine shaft. The limestone part is the ore-bearing horizon nearby.

The top of the middle unit of a 6 m section is usually marked by a thin shale. The megascopic texture is similar to that of the upper-unit, but is of a definite brown color.

The lower unit of about 8 m consists of brown, dense to oolitic limestone. It contains thin grey or black shale partings.

3. Upper part of Downeys Bluff Limestone Formation

The Bethel Sandstone Formation which overlies the Downeys Bluff is essentially a white medium-grained quartzose sandstone which contains minor amounts of shale or coal as thin partings. In contrast to the Spar Mountain and Rosiclare Sandstone Members, it does not contain much calcareous cement (less than 5%) between quartz sand grains. The basal 1 m of the Formation is cross-bedded and oscillation ripple-marked. Throughout much of the Hardin County, the base of the Bethel Formation consists of green shale varying from 3 to 7 m in thickness; however, this shale does not occur in the Oxford and Minerva No. 1 mines; it became apparently removed through subaqueous erosion.

In the field, the Downeys Bluff Limestone Member has been described as a light to brown crystalline limestone with an oolitic phase. Microscopic examination shows that in the upper 5 m of this Member found in the Oxford and the Minerva No. 1 Mines, bioclasts predominate over oolites, whereas oolites predominate over bioclasts in the two other ore-bearing horizons. Locally, the uppermost part of the Formation contains chert nodules and lenses which are of diagenetic replacement origin. The lower half of the Formation consists of light brown oolitic and bioclastic limestones.

The cross-beddings and ripple-marks found in three ore bearing horizons all indicate generally a well aerated, shallow marine, predominantly above wave base, and relatively turbulent environment of deposition. Occasional fluctuations of the sea level could be visualized through cyclic occurrences of sandstones and shales and primary sedimentary structures, such as large scale features of cut-and-fill, slumps and breccias found in them. Author's observation in the Mines and Quarries indicate that localization of ore bodies are closely associated with such primary sedimentary structures. It is interesting that the distribution of most of the mineralization coincides with the direction of paleocurrents and deltaic erosion-channels described in POTTER and PETTIJOHN (1963, Figs. 8-23 and 9-7).

Recognition and distribution of such structures are very important in understanding ore genesis of the district and in further exploration.

Author's Work

Work recently started involves a detailed systematic study of the distribution of trace elements in barites and fluorites. With the financial support of Boston University Graduate School, the summer season of 1970-71 was spent mainly in the Minerva No. 1 Mine where a systematic sampling program of the northeastern portion of the Mine was accomplished. Detailed geochemical and petrographic work is being currently conducted on those samples. During this summer, the author will spend about 3 weeks in the Mine to collect more field data and samples. The present proposal will involve in part extending similar work to the rest of this Mine as well as other surrounding mines and showings (especially W.L. Davis-Deardorff, Hill and Oxford Mines) in the hope of arriving at an integrated picture for the region. The choice of the mines to be investigated and the rationale for that choice is given in the section entitled "Plan of this Investigation".

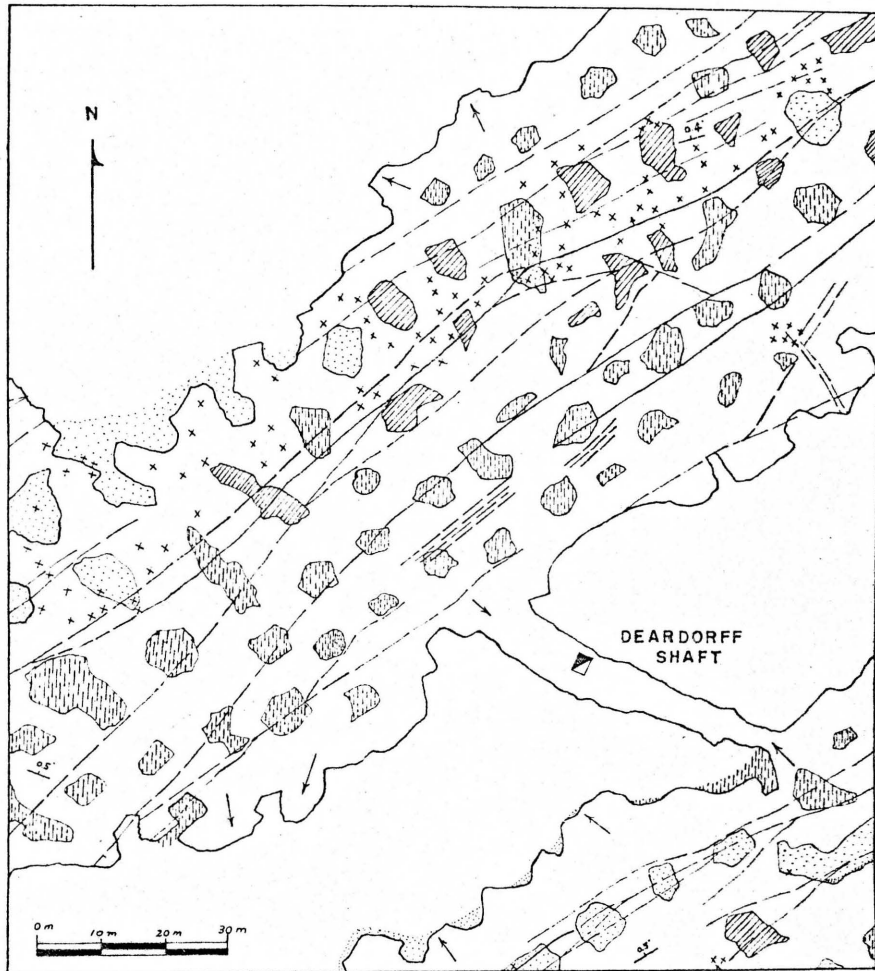
In the following few paragraphs, the salient parts of the detail of the geology of one of the better investigated mines, namely, the Deardorff, are given. Further details for the other mines are given in Appendix I. Studies on structures found in the periphery of and within ore bodies of Deardorff, Hill and Oxford Mines and petrology of the ore-bearing rocks have been published by the author and his co-workers (AMSTUTZ, RAMDOHR, EL BAZ and PARK, 1964; PARK and AMSTUTZ, 1968; PARK, 1967; PARK and SCHOT, 1968 a and b).

Deardorff Mine (Location: NE 1/4 of Sec. 34, T. 11 S., R. 9 E.)

The host Fredonia Limestone Member consists largely of oosparites, indicating high-energy environment during the depositional period. The overlying Spar Mountain Sandstone (0-2 m thick) consists of lenticular bodies of well sorted calcareous sandstones, the calcareous part being bituminous micrite.

The Deardorff ore body is about 200 m wide, up to 10 m in thickness and about 700 m long.

Figure 3 is a part of the Deardorff Mine, which shows fault and fracture systems, ore zoning and pinch out directions of ore layers. Numerous vertical



MAP OF PART OF W.L. DAVIS-DEARDORFF MINE,
SOUTHERN ILLINOIS FLUORSPAR DISTRICT

LEGEND

SPAR-SULFIDE ORE -----		HIGHLY SILICEOUS BRECCIATED AREA ---	
QUARTZ-SPAR-SULFIDE ORE ----		PINCHED-OUT DIRECTION OF ORE BANDS-	
QUARTZ-SULFIDES ORE -----		STRIKE AND DIP OF DOLOMITE -----	
MINOR FAULT -----		PILLAR -----	
FRACTURE -----		LIMIT OF MINED AREA -----	

Fig. 3. Fracture system, ore occurrence and zoning, and pinch-out directions of ore layers, part of the Deardorff Mine.

fracture planes strike in a N 40° - 60° E direction which is the strike of the regional fault system. Several normal faults with a displacement of up to 4 m at the northeastern part of the Mine are filled with massive fluorite and calcite.

It has been supposed by previous workers of the district that the numerous faults and fractures found in the mines are the "channel-ways" of the ascending ore solution. However, we showed that these fractures could not be the "channel-ways", since most of them do not extend downward beyond the bottom of the ore zones (AMSTUTZ and PARK, 1967). Several oval-shaped breccia areas, such as found in the Hill, Green and Minerva No. 1 Mines, may have been the channel-ways as postulated by BRECKE (1962) and GROGAN and BRADBURY (1968). HUGHES (1967) showed that there exists a trace element zoning in sulfides around the Hill breccia area which he interpreted as channel. Positive proof that the breccia areas were channel-ways for ascending ore solutions is, however, lacking. In this proposed project, some trace elements in fluorites and barites around Minerva breccia area will be investigated systematically, if there is indeed a zoning pattern like in sulfides.

The author (1968) has recognized mineralogical zoning in Deardorff ore body, although it is not distinct. Figure 4 shows the basic configuration of the ore occurrence and lateral and vertical zoning found in the mine. The ore and "coon-tail" layers have distinct position in space according to their mineralogy as shown in Fig. 4. Fluorite-sphalerite layers occur generally at the lower portion of the ore zone, whereas quartz-fluorite-sphalerite layers and quartz-sulfide (sphalerite and galena) layers occur in the upper part. The top quartz-sulfide and quartz layers do not show "coon-tail" feature, but they occur in layered, massive, or undulating patterns or as cavity-fillings, or are associated with brecciated carbonate rocks.

Certain ore layers in the mine are called "coon-tail" by the local miners. This coon-tail-like pattern consists of an alternation of thin layers of fluorite and sphalerite. Locally galena, quartz and carbonates may occur disseminated in "coon-tail". Certain barite layers in Minerva No. 1 Mine exhibit coon-tail-like pattern due to the alternation of grain size. The average thickness of an individual layer measures about 0.5-1.5 cm and total thickness of the "coon-tail" zones may be up to 5 m. "Coon-tails" are space-rhythmites and are usually cross-bedded.

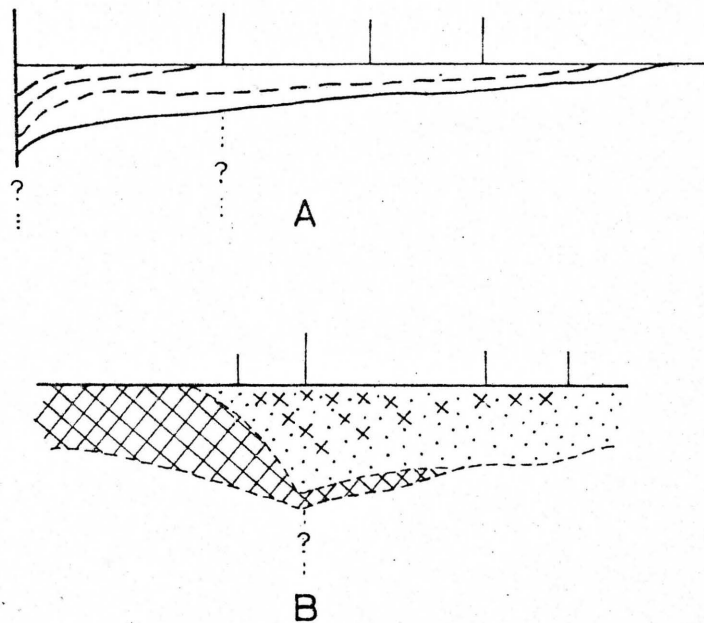


Fig. 4. A. Generalized configuration of cross-bedded ore layers and associated fracture system. The width of the ore beds may reach up to several tens of meters.

B. Basic configuration of lateral and vertical zoning of ore body in the Deardorff Mine. Cross-hatched portion is a zone consisting of fluorite, sphalerite, and subordinate galena cross-beds; dotted portion of siliceous zone. Crosses indicate siliceous breccia zone. This figure was largely drawn from observation near Pillar 223, about 130 m east of the Deardorff shaft.

Because of their structure, texture and mineralogy, these "coon-tail" layers have been the subject of much discussion. They were thought by earlier workers (BASTIN, 1931; CURRIER, 1937; GROGAN, 1949; BRECKE, 1962) to have been formed by metasomatic replacement or by "solvate apposition metasomatism" of HANUS (1960). The cross-bedded nature of the "coon-tail" has been explained to be inheritant from oolitic cross-bedded limestone. In 1967, we have pointed out difficulties in explaining the mechanism of the "coon-tail" formation by metasomatic replacement and proposed that these were normal depositional rhythmites which have subsequently recrystallized (AMSTUTZ and PARK, 1967).

Numerous vugs and open fractures of a few centimeters in size occur within and in the near vicinity of the ore layers. A generalized paragenetic sequence found in vugs and open-spaces, from the earlier to the later mineral, is as follows: sphalerite (galena)-fluorite-smoky quartz-bitumen-galena (sphalerite)-scalenoedral calcite-barite.

"Coon-tail" like cross-bedded barite layers frequently found at the northeastern area of the Minerva No. 1 Mine are one of the most interesting ore structures the author has observed recently; "coon-tails" consist of alternating layers of about 1 cm thick each of colloform barites (white) and sand-sized impure barites with disseminated dolomite (grey to dark grey). Our study shows that colloform layers are due to dissolution-recrystallization of finer barite layers. During and after the latest stages of colloform barite layers, two generations of fluorite occupy the tops of colloform. After this, there must have been several solution-migration activities which affected all above layers, because 1) locally strontian witherites and strontianite have crystallized in the cavities in which colloform barites occupied previously and 2) large stylolites cut through "coon-tails". During the investigation of the present proposal, we want to study these features in detail.

The author's previous work (PARK, 1968 and 1971) on Deardorff, Hill and Oxford Mines are summarized in the following few paragraphs and results on paragenesis is given in the next sub-section, "Diagenetic and Epigenetic Processes".

Several features known previously as secondary slump or collapse structures prove to be primary scour-and-fill channels which have modified by the ore solution later. The relationships between such features and fluorite-sphalerite ores indicate that the latter have been deposited during and after the formation of such channels.

Numerous occurrences of stylolitic seams in the host carbonate rocks and ore layers, not only in the Cave-In-Rock district but also in other districts of Mississippi Valley Type deposits, led to a detailed investigation of them (AMSTUTZ and PARK, 1967; PARK and SCHOT, 1968 a and b; SCHOT and PARK, 1968). Stylolites in limestone host rocks are loci of accumulation of many authigenic and ore minerals and material such as bituminous material, clay minerals, quartz, dolomite, albite, sulfides and fluorite. The author's work has shown that stylolites in limestones from tectonically stable cratonic areas form normally before complete cementation stage of the limestones. The reason why stylolites are so abundant near and within ore bodies of the Mississippi Valley Type is not clear, but all evidence indicates that they have formed in the area of mixing of Na-Cl type ore solutions and ground water and the intensity of stylolitization depends on numerous factors including lithostatic unidirectional pressure, grain fabric relationships including porosity and permeability, composition of migrating fluids including Eh and pH, rate of cementation, environment of deposition and subsequent burial evolution, etc. Stylolites prove to be an important structure from which valuable information on ore genesis and diagenesis can be found.

From the observation and evidence accumulated by the previous workers (see list of literature above) and the author, it suggests that the present form of stratiform ore deposits of the Cave-In-Rock district is a cumulative result of a series of different ore mineral formations (polymetallic pulsation of ore solutions, rather than a single pulsation) emplaced largely during the late diagenesis of the host carbonate rocks; i.e., the stages when the primary carbonate sediments have not undergone complete cementation (porosity much higher than 10-15%), thus the host rocks having had sufficient permeability for ore solutions to invade. Several newly on-coming ore solutions may have dissolved and redeposited some ores already precipitated; this makes a study of paragenetic sequence complicated. The author (1968) suggested that ores in vugs and fault planes are generally later than those found disseminated in the host rocks.

As for the source of ore constituents, the author believes as other investigators of the district (HALL and FRIEDMAN, 1963, in part; HEYL, 1965; PINCKNEY, 1966) that they were transported by warm saline formation waters or non-magmatic hypogene solutions derived from within the sedimentary rocks of the Illinois Basin. Thick Devonian New Albany Shale deserves attention in this regard.

In an author's recent work (PARK, 1971), he has attempted to answer some of the following questions of ore genesis of the Cave-In-Rock deposits; 1) How did F anions migrate in porous limestones to precipitate fluorite? 2) What are the geologically reasonable physico-chemical environments and important factors under which fluorite or a suite of ore minerals is stable and precipitated? 3) If stable and precipitated under given conditions, how much ore solution is required for a given tonnage of ore? 4) How long would it require to precipitate a given tonnage of ore under a reasonable hydrological condition?

From simple solubility considerations of fluorite, it was shown by the author (PARK, 1971) that solutions percolating through porous limestones with a concentration of the order of 10 ppm fluorine, which is not very unusual amount in some brines of oil fields (WHITE et al., 1963 and FLEISCHER and ROBINSON, 1963), can be regarded as ore forming solutions capable of precipitating large important fluorite deposits of low temperature origin.

Mass transfer considerations with a simple flow model, based on fluid inclusion studies of GROGAN and SHRODE (1952), HALL and FRIEDMAN (1963), and PINCKNEY and HAFFTY (1970), solubility data of STRÜBEL (1965), and reasonable hydrological assumptions, indicated that $10^7 - 10^8$ liters of such ore solutions would be required to precipitate 1 ton of fluorite through simple cooling from 100° to 20° C and a time span of $10^7 - 10^8$ years to form an ore body of 60% grade of 100-500 meters long. Rate of precipitation, thus, must have been slow compared with ore solution velocity.

Mixing of two ore solutions (regarded as a reasonable mechanism of ore precipitation from geochemical point of view, i.e., HOLLAND, 1967 and SKINNER, 1967), both almost saturated with respect of fluorite, but with different ratios of calcium to fluorine could result somewhat larger and faster precipitation of fluorite, but the order of magnitude is shown to be not significantly different from above figures. The problem of mixing mechanism which is to be looked ^{at} more carefully is that continuous mixing of two or perhaps more apparently unrelated solutions during a long period of mineralization is hydrologically difficult to realize. Detailed structural and petrographic studies as proposed in the present investigation may bring out some insight on this problem.

Petrographic investigation of the author (PARK, 1968 and 1971) showed that fluorite and silica, in the order of 100:1 ratio, have crystallized more or less simultaneously. Whether fluorine was complexed with silicate

rings and chains (BUERGER, 1948; ELLIS and MAHON, 1964; EITEL, 1966) during migration of ore solutions, or complexed in organic compounds (KRANZ, 1966) requires a thorough investigation in the future.

Diagenetic and Epigenetic Processes including Ore Genesis

Introduction:

The term "diagenesis" (von GÜMBEL, 1868) has been used in different senses by various workers (WALTHER, 1894; PETTIJOHN, 1957; RUCHIN, 1958; TWENHOFEL, 1961; CHILINGAR, BISSEL and WOLF, 1967) and at times brought confusion and misunderstandings in the recent literature especially dealing with the stratiform ore deposits.

Diagenesis is: All the endogenic physico-chemical, biological and physical changes occurring in sediments between the time of deposition and the time at which complete lithification through compaction and virtually complete cementation takes place. Epigenesis refers to such changes taking place after diagenesis by either endogenic or exogenic causes.

During the last 20 years, several attempts have been made to subdivide diagenetic processes into stages. Well-defined subdivisions are a very important first order approach in reconstructing the diagenetic history of a particular rock. They have been constructed on the basis of the chemical and mineralogical changes (TEODOROVICH, 1961; PACKHAM and CROOK, 1960; DAPPLES, 1962; LAND, 1967; MÜLLER, 1967), the depth of burial (KESSLER, 1922; RUCHIN, 1958; in part FAIRBRIDGE, 1967), the porosity (ENGELHARDT, 1960 and 1967; MÜLLER, 1967), or the fabric relationships (SANDER, 1936 and 1950; WOLF, 1963; AMSTUTZ et al., 1964; AMSTUTZ and PARK, 1971).

It is not correct to apply the overburden concept on the basis of fabric observations especially of carbonate rocks. In so far as there is no corresponding relationship between fabric and the depth of burial, subdivisions based on the fabric relationships appear to be most practical, especially the relations between carbonate rocks. Since physico-chemical causes of various cement types, replacement and recrystallization processes of carbonate rocks, are not well understood at present, careful studies of paragenetic events are satisfactory in ore deposit investigations. For the oolitic limestone host rocks of the southern Illinois district, we have found the following subdivisions of diagenesis practical in reconstructing paragenetic events (PARK, 1968;

AMSTUTZ and PARK, 1971). Each subdivisions is based on the sedimentological and fabric characteristics: 1. Depositional stage; 2. Early Cementation stage; 3. Intermediate Cementation stage; 4. Late Cementation stage; and 5. Epigenetic stage.

A short summary of the petrologic investigation (PARK, 1968) of the host carbonate rocks and ores follows.

Fabric Trends:

Using Folk's (1959 and 1965) terminology, the author (PARK, 1968) has shown that host oosparites change in their fabric properties towards an aggrading coalescive neomorphism as shown in Fig. 5. The fabric feature (2) of Fig. 5 is most frequently observed within a few cm from the ore layers. If neomorphism and replacement proceeded further, the fabric feature (3) is typical. The individual grains drawn in (3) of the same figure may consist either of carbonates, fluorite or quartz.

In contrast to the oosparites, micrites and dolomicrites change their fabric properties in the following sequence: dolomicrites → dolomicrosparites → porphyrotopic fabrics (terminology after FRIEDMAN, 1965) → poikilotopic fabrics. Figure 6 (PARK, 1968, Fig. 151) shows these fabric changes which accompany mineralogic changes.

Paragenetic Sequence:

Based on the field and the careful petrographic work, a simplified paragenetic crystallization sequence of the host carbonate rocks and the ore-bearing rocks has been devised as shown in Fig. 7 (Fig. 3 of AMSTUTZ and PARK, 1971). This represents combined paragenetic sequences found in the Deardorff, Hill and Oxford Mines and certainly needs further detailed and extended work from other mines. The author will continue along this line of research in the present investigation. Geochemical and hydrological considerations of the deposits would have to be based on an elaborate paragenetic sequence. The sequence of Fig. 7 includes not only the mineral deposition during the various diagenetic pore-filling cementation stages and epigenetic stages, but also of the recrystallized and remobilized material.

Careful study and consideration of the superposition rule and convex-concave relationships were given, in addition to the geochemical and petrologic evidence, in judging the sequential order of the various mineral formations.

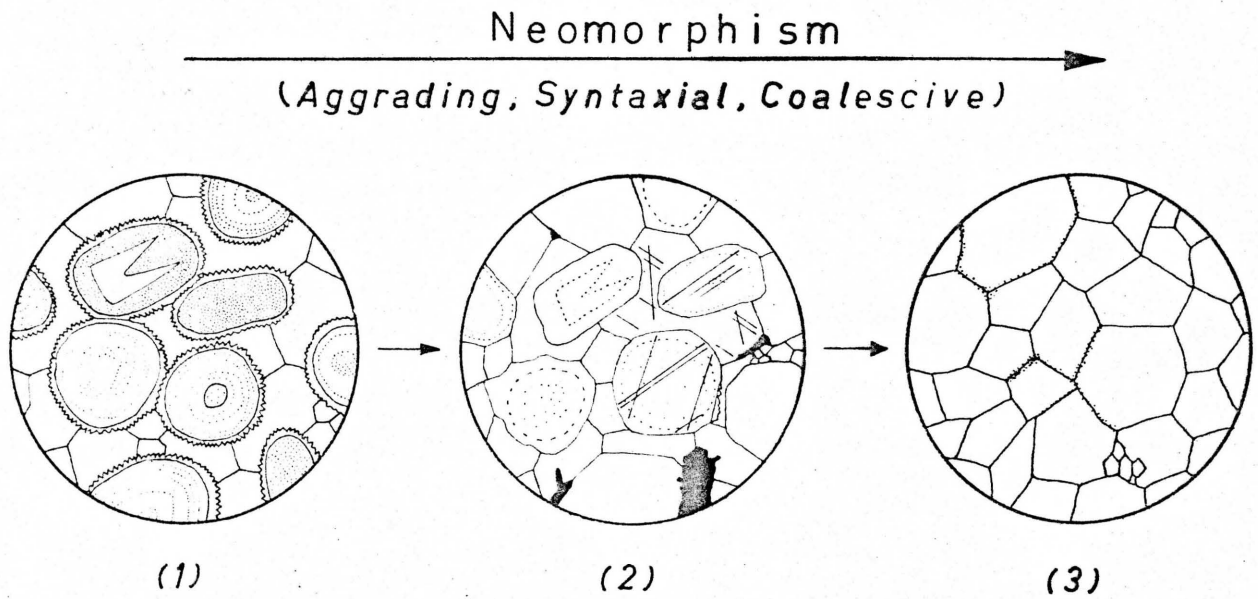


Fig. 5. Aggrading, syntaxial, coalescive neomorphism in oosparites, as their fabrics modify in time and space. Black grains in (2) indicate quartz.

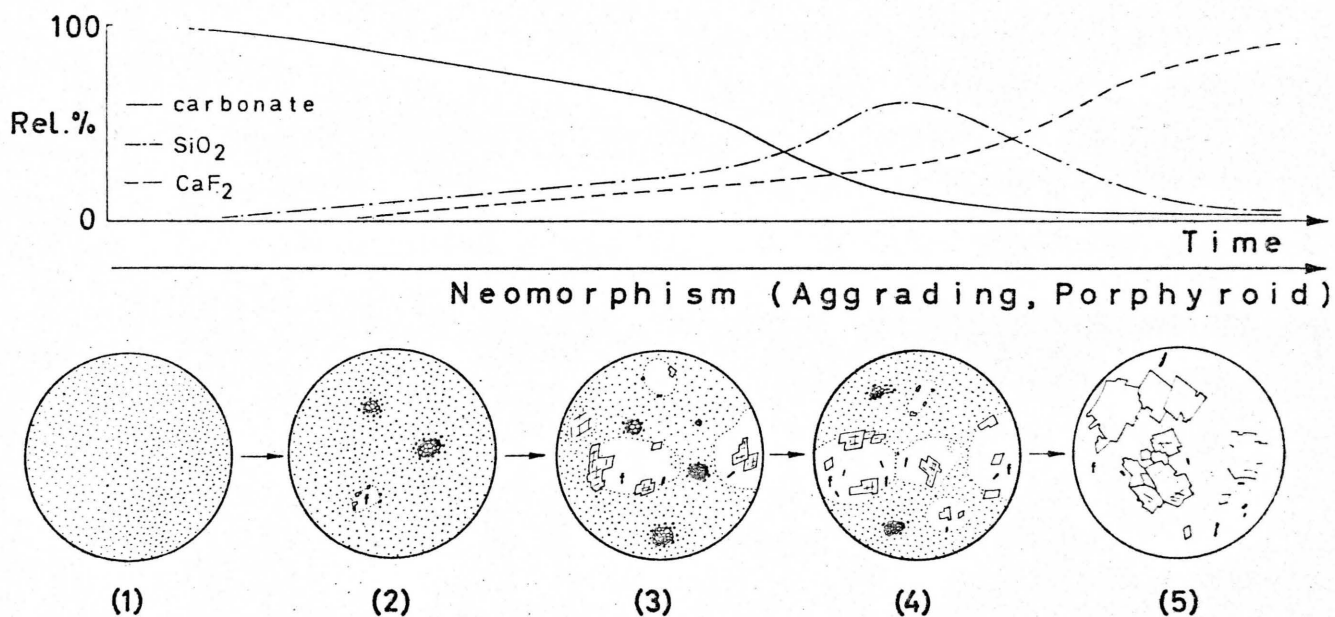


Fig. 6. Change of the relative percentage of carbonates, quartz and fluorite in relation to time and to the neomorphic fabrics.

- 1: micron-sized equigranular idiotopic micrites or microsparites.
 - 2: micron to 50 micron-sized inequigranular porphyrotopic fabrics.
 - 3: poikilotopic to porphyrotopic fabrics.
 - 4: porphyrotopic to poikilotopic fabrics.
 - 5: idio-poikilotopic fabrics of dolomite in the fluorite groundmass.
- f: fluorite.

small black bars in 3, 4, and 5: doubly terminated quartz.

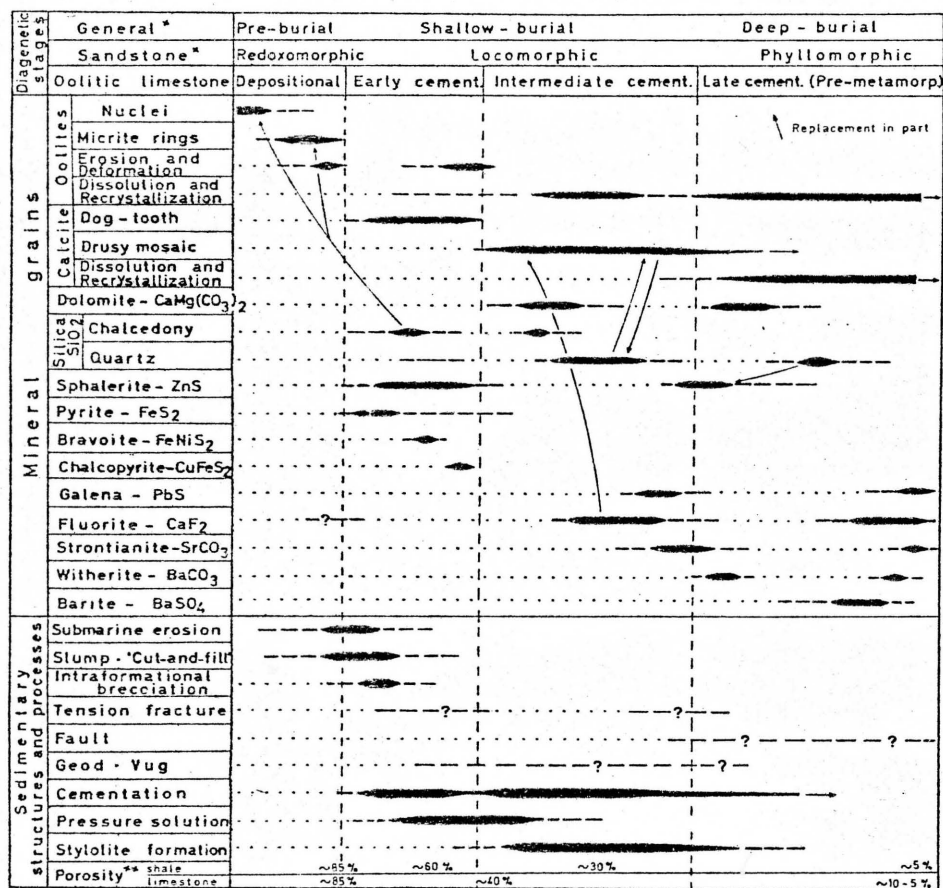


Fig. 7. Paragenetic sequence of the minerals and of the various sedimentary structure formations, Deardorff, Hill, and Oxford Mines, Cave-In-Rock district, Illinois. The thicker portion of a bar indicates the main stage of formation, whereas the initial stages of formation are shown by the thinning of a bar (after AMSTUTZ and PARK, 1971). Late Cementation stage includes in part Epigenetic stage.

* Subdivisions of diagenesis proposed by DAPPLES (1959 and 1962).

** Porosity values for shale after MÜLLER (1967).

In doing so, the following standard books and articles on petrofabrics were consulted: SORBY (1908), CAYEUX (1935), SANDER (1936 and 1950), SHROCK (1948), GILBERT and TURNER (1949), FAIRBAIRN (1949), BASTIN (1950), GRAF and LAMAR (1950), KAMB (1959), VOLL (1960), SHUMSKII (1964), GLOVER (1964), SMITH (1964), STANTON (1964), AMSTUTZ (1965), BYRNE (1965), GRIGOREV (1965), KRETZ (1966), EWERS (1967).

An extensive study by the author (PARK, 1968) has shown that the localization of ore minerals through open-space filling and replacement is largely controlled by the composition, crystallinity of the host carbonates and other sedimentological factors.

A summary of the paragenetic sequence found in the Deardorff, Hill and Oxford Mines is given in Appendix II.

Plan of Investigation

The proposed investigation will include: 1. Field studies; 2. Petrological studies; 3. Geochemical studies especially the determination of Sr/Ca ratios in fluorites and barites. These will be closely coordinated and evaluated in conjunction with the author's previous work.

Mines to be Investigated

Among the bedding replacement ore bodies, four mines (Deardorff, Hill, Oxford, and Minerva No. 1) are chosen because of two reasons: 1. they comprise all three main ore horizons, so that observations can be made and evaluated more meaningfully; 2. geology of these mines is fairly well known, so that sampling bias may be reduced.

Although the Deardorff, Hill and Oxford Mines are either closed or inaccessible at present, the author has previously studied some of the field relationships in them and obtained a large number of well chosen samples. Current work by the author, partly supported by a grant from the Graduate School of Boston University resulted in collecting samples from the northeastern 1/4 and the southwestern end of the Minerva No. 1 Mine. In order to complete the current work, it is necessary to study and collect samples from the remaining gap at the Minerva No. 1 Mine. The Minerva Oil Company which owns the Mine has kindly allowed us to work in the underground (Mongommery and Saxy, Personal communication).

A few fluorite and barite samples for analytical work have been

collected during the summer, 1970 from 5 vein type deposits in the district. They were, however, restricted to old workings within and close to the vicinity of the Hicks Dome. In order to investigate the regional Sr/Ba variation, more samples from vein type deposits along Rosiclare fault system will have to be collected.

Mapping

The first 3 mines, which are now inaccessible, have been mapped by the author. Detailed mapping of the Minerva No. 1 Mine will be conducted in order to correlate the result with other mines and to plan and coordinate it with laboratory study.

Since the geometry of the Minerva No. 1 ore body is almost horizontal, thin (normally not more than 5 m in thickness), channel-like, narrow and long (total length of the Mine about 4 miles), most of the mapping will have to be done on several cross-sections of 1 m = 1 cm in scale, perpendicular to the long axis of the ore body. Because mine walls and pillars are covered with dust, they will be scrubbed with wire brush and washed with bucket water. Five well chosen cross-sections of the Mine will be mapped at the Bethel horizon and several sections at the newly developed Levias and Fredonia horizons. In the maps we plan to show lithology, degree of recrystallization and alteration near the ore layers, changes in grades of ore, structures of primary and secondary origin, mineralogic variation within ore body, and ore layer features. Any structures which appear important in interpreting ore genesis will be photographed and drawn in detail.

Sampling

Careful sampling will be most essential and critical for laboratory investigation. Sampling will be carried out in such a way that an over all picture of the ore body can be represented as much as possible. At several important locations sampling will be done to represent a mine wall or pillar.

Samples will be collected to enable us to determine any significant vertical and horizontal differences in the host rock facies and in the trace element content in different generations of fluorites and barites. As we map along the chosen cross-sections, samples will be taken from above, within and below the ore layers including transition zones, in order to investigate petrographic, mineralogic, and paragenetic changes. Previous sampling in the Mine indicates that we will need to collect about 5-10 samples from each of the critical

localities. The location of samples will be recorded on the map as we proceed mapping. Oriented samples will be collected in order to study geopetal features, if any.

Sampling of the fluorite and barite is rather critical, since the author's current work indicates the presence of more than 2 generations of each of them. When typical structures and ore layers are found, samples with large surface areas will be collected for detailed investigation.

Several newly opened mines (M.F. Oxford No. 7 Mine and Spivey development of the former Green Mine) will be visited where preliminary field studies and sampling will be conducted.

Petrologic Studies

About 200 thin-sections and 50 polished-thin sections of sulfides will be made.

These will be used to investigate: 1) the depositional environments of the limestone host rocks, 2) the petrology of the overlying sandstone units and the effect of the calcareous sediments and the mineralization immediately below, 3) the diagenetic history of the host limestones, 4) range of porosity (thus inferred permeability), 5) sulfide mineralogy and textures, 6) grain fabric relations of the samples to be analyzed, and 7) paragenesis of ore minerals and whether mineralization took place through a single pulsation or through polymetallic multipulsation.

Limestone host rocks sampled near ore layers which show no ore minerals and no sign of recrystallization will be studied first in order to establish a base for studying variations in fabric characteristics due to mineralization. Intensively recrystallized host carbonate rocks and granular fluorite and sphalerite rocks will be studied using the Universal-stage in order to identify Sr-, Ba- carbonates and to study degree of recrystallization by measuring grain size, grain orientation, and the angle of triple junctions of grain boundaries. The author's preliminary investigation points encouragingly to the possibility of quantitatively expressing the degree of recrystallization using these measurements.

In order to study the composition and stages of crystallization of carbonate minerals in limestone host rocks and ore rocks, thin sections will be stained with $K_3Fe(CN)_6$ -HCl-Alizarin RS solution. Staining techniques are

well described by DICKSON (1966). In studying carbonate sections, modern knowledge of carbonate petrology will be employed. Application of such knowledge to the Mississippi Valley type deposits would result in a new insight on the problems of ore genesis, as was shown by the author (PARK and SCHOT, 1968a; PARK, 1968; AMSTUTZ and PARK, 1971) and by several others (GERMAN, 1966; JACKSON and BEALES, 1967.) During the last 20 years, great advances in carbonate sedimentology were made. Publications relevant to the present investigation include: GRAF and LAMAR, 1950; BATHURST, 1958, 1964 and 1971; WEYL, 1958; FOLK, 1965; FRIEDMAN, 1965 and 1966; MATHEWS, 1966; BERNER, 1966, 1968 and 1971; FRIEDMAN and SANDERS, 1967; SANDERS and FRIEDMAN, 1967; HSU, 1967; SCHMALZ, 1967; BRICKER, 1971.

A large number of thin sections will be investigated under the cathodoluminoscope attached to a microscope. The author's previous examination of carbonate sections, fluorites, barites and sphalerites showed an unusual amount of detail in textures and compositional variations, which were not apparent with a normal polarized microscope. These include micro-scale growth zoning, veining, recrystallization and variations in trace element and Rare Earth content. Several publications on the application of cathodoluminoscope in petrology indicate very promising results (SMITH and STENSTROM, 1965; SIPPEL and GLOVER, 1965; LONG and AGRELL, 1965; WEBER et al., 1967; SIPPEL, 1968; HERZOG et al., 1970; KNISELEY et al., 1969; POTOSKY and KOPP, 1970; BHALLA and WHITE, 1970; FREEMAN, 1971; KASTNER, 1971).

Chemical Analysis

Atomic absorption technique will be used to analyze approximately 200 fluorite specimens. The fluorite will be separated by heavy liquids, examined microscopically and hand picked if necessary. Fluorite will be dissolved and Sr concentrated through ion-exchanger using radio-tracer method. The Department of Geology and Geophysics of M.I.T. has kindly consented to allow us to use the necessary equipment and facilities to undertake the proposed analysis of fluorite. Presently, fluorites are being analyzed for Sr and R.E. at the geochronology laboratory by one of our doctoral candidates with the help and supervision of Professor W.H. Pinson, Jr. of M.I.T. Preliminary results indicate that fluorites from Minerva No. 1 Mine contain between 40-150 ppm Sr.

Sr, Ba, and Ca analysis of approximately 200 barite samples will be done by flame photometry at the Department of Chemistry, Boston University. A method

of sample preparation and analysis developed by PUCHELT (1964) will be used. A preliminary analysis of Ba, Sr and Ca in barites by the author shows the following variation of $\text{BaSO}_4 = 95.60-98.15$ wt %, $\text{SrO} = 0.63-0.71$ wt %, and $\text{CaO} = 0.33-2.13$ wt %, with the Sr/Ba ratio from 0.007 to 0.01.

In addition to chemical analysis for fluorites and barites, x-ray diffraction studies will be carried out at the Department of Geology, Boston University as needed.

A few selected barite samples will be analyzed for Sr and Ca with electron probe, in order to detect any zoning on a microscale, and in light of this to evaluate the results of flame photometric analyses. Since fluorites contain Sr below the detection limit, cathod-luminescope will be the only available means to detect any microscale compositional variation. The probe analyses will be done at the Department of Geological Sciences, Harvard University and at the Mineralogical Institute, University of Heidelberg where the author has conducted a number of such analyses previously.

The purpose of the chemical analysis is to: 1) determine the Sr content in fluorites, and Ba, Sr and Ca content in barites of different generations, 2) determine any systematic variations of the above trace elements within the Minerva No. 1 ore body as well as on a regional scale, 3) compare similar analyses on fluorites and barites with different geological origins (data of STARKE, 1964; PUCHELT and MÜLLER, 1964; PUCHELT, 1967; and HEINRICH and VIAN, 1967), and 4) interpret the results regarding the physico-chemical interaction of ore solutions(s) with host carbonate rocks and paleohydrologic conditions of ore solutions(s).

Evaluation of Results

The purpose of this proposal is to integrate the results of the present investigation with those of past studies in order to arrive at a reasonable insight regarding the origin of the stratified deposits of the Cave-In-Rock district. A combined evaluation of different lines of evidence should provide for a better understanding of the ore genesis of the district and aid in further exploration work in the area. It is hoped that this study will open the door for further integrated geochemical and petrological investigations.

The chemical analysis of fluorites will be evaluated, in addition to the consideration of the field and petrographic data, in relation to the solubility

experiments (ELLIS and MAHON, 1964; STRÜBEL, 1965), thermodynamic calculation (CADEK et al., 1965 and 1968; HOLLAND, 1967; HELGESON, 1964 and 1970; MALININ, 1963 and 1970), the fluid inclusion studies (GROGAN and SHRODE, 1952; HALL and FRIEDMAN, 1963; PINCKNEY and HAFFTY, 1970), and the hydrogeochemical mass transfer considerations (HUBBERT, 1940; TODD, 1959; ROEDDER, 1960; HELGESON, 1970; PLUMMER, 1971; PARK, 1971).

The chemical analyses of barites probably lend themselves to a more rigorous evaluation than the fluorites, since the Sr/Ba studies of barites (GUNDLACH, 1959; STARKE, 1964; HANOR, 1966; PUCHELT, 1967; CARDICH-LOARTE and SCHROLL, 1971), their solubility and the Sr distribution in them (UCHAMEYSHBILI et al., 1966; STRÜBEL, 1967; MALININ et al., 1969) are relatively better known.

Facilities

Storage space and general laboratory equipment, including all usual facilities (sinks, gas, compressed air, shelving, benches, etc.) are available. Major pieces of equipment and laboratories currently in use by the author in the Department of Geology, Boston University, include:

1. Research microscope laboratory - Contains research petrographic microscopes and accessory equipment including universal stages and equipment for polished section investigations, Leitz microphotographic equipment, an Eberbach thin-section storage cabinet, Wards storage cabinets. One cabinet per year will be supplied by the Department of Geology and one per year is budgeted from the NSF funds.
2. Thin-section and polished-section preparation laboratories - Contains two large saws and two additional trim saws for slicing rocks, laps and glass plates for grinding, vacuum impregnator for preparation of thin-sections of porous rocks, acetate peel preparation materials, an AB Polimet fine polishing apparatus, an AB specimen mount presser, and a large vibro-lap.
3. Well-equipped drafting room.
4. LeMaire jaw crusher, LeMaire pulverizer, and sieves.
5. Frantz magnetic and centrifuge separators plus equipment for heavy liquid separation.
6. X-ray diffraction and fluorescent equipment including a large assortment of accessories.

7. Vreeland spectroscope.
 8. Automatic mortar and pestle.
 9. Olivetti desk computer and Monroe calculator (also available are two IBM 360/50 computers of the Boston University Computer Center).
 10. Mettler balance.
 11. Leicaflex with wide angle lens for taking pictures of the mine wall.
- Unicam SP-90 atomic absorption spectrophotometer for analysis of barites is available at the Department of Chemistry, Boston University.

Facilities of the Geochronology Laboratory, Department of Geology and Geophysics, M.I.T. will be used for the analysis of Sr in fluorites (Pinson, Personal communication).

Electron microprobes are available for use at Harvard University and at University of Heidelberg.

The talents of Mr. Harold Thompson, technician of the Department of Geological Sciences, Harvard University, for thin sections and probe mounts and Mr. Heinrich Lämmler, technician of the Mineralogy Institute, University of Heidelberg, for polished-sections can be utilized to prepare excellent sections.

Personnel

Principal Investigator:

Won C. Park
Assistant Professor of Geology

Education:

University of Heidelberg - Ph.D., Mineralogy, 1968
University of Missouri at Rolla - M.S., Geology, 1962
Seoul National University - B.S., Geology, 1960

Academic Experience:

Assistant Professor of Geology, Boston University, 1969-present
Wissenschaftlicher Assistent, Mineralogisch-Petrographisches Institut, University of Heidelberg, 1966-1969

Field Experience:

- Search for host granites of the monazite-bearing fluvial sands, southwestern Korea (B.S. thesis), 1958-1959
- Economic ore deposit trip to S.E. Missouri barite and lead belt, S. Illinois, Arkansas bauxite and barite deposits, N. Missouri coal field, early summer, 1961
- Study of glauconitic breccias, Decaterville, Mo., early summer, 1961
- Ore deposit investigation of the Hill, Deardorff, Oxford, Crystal and Minerva No. 1 Mines, S. Illinois, summers, 1961-1962
- Exploration activities in Yukon and British Columbia, Canada, summers, 1963-1964
- Field excursion to Swiss Alps, 4 weeks, autumn, 1965
- Investigation of suevite glasses, Ris Basin, Babaria, Germany, spring, 1966
- Ore deposit trip to Rammelsberg, Ramsbeck, Meggen, and Lahn Dill district, Germany, autumn, 1966
- Volcanology and modern carbonate sedimentation field excursion to Canary Islands, 3 weeks, winter, 1967
- Stratigraphy and sulfide-sulfosalts investigation of the Triassic Dolomites, Lengenbach, Binntal, Switzerland. A month each, spring and autumn, 1968 and spring, 1969
- Ore deposits excursion to Adirondacks and Pennsylvania, spring, 1970
- Ore deposits investigation of the Ni-pyrrhotite and Zn-Cu deposits, central eastern Maine, spring and early summer, 1970
- Stratigraphy, lithology, tectonics and sulfide-sulfosalts investigation, Binntal Valley, Switzerland, 6 weeks, summer, 1971
- St. Moris zinc-copper deposit excursion, N.E. of Grenoble, summer, 1971

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Research Assistant:

One graduate student (doctoral candidate) will be associated with the project as a research assistant on a half-time basis during two academic years and on a full-time basis for two months during two summers.

BUDGET SUMMARY*

A.	SALARIES AND WAGES	
1.	Principal Investigator	\$ 5,930
2.	Research Assistant	9,000
3.	Secretarial - Clerical	<u>800</u>
	Total Salaries and Wages	\$15,730
B.	FRINGE BENEFITS	
	(15% of A 1 and 10% of A 3)	<u>970</u>
	Total Salaries, Wages and Fringe Benefits (A + B)	\$16,700
C.	PERMANENT EQUIPMENT	4,310
D.	EXPENDABLE SUPPLIES AND EQUIPMENT	2,103
E.	TRAVEL	400
F.	PUBLICATION COSTS	200
G.	OTHER COSTS	<u>3,490</u>
H.	TOTAL DIRECT COSTS	\$27,203
I.	INDIRECT COSTS	<u>7,347</u>
	1. On Campus - 63.60% of 7,800	
	2. Off Campus - 30.09% of 7,930	
J.	TOTAL COSTS (H AND I)	\$34,550

* See following text for itemized budget by year.

RESEARCH GRANT PROPOSAL BUDGET

Year Beginning February, 1973

Budget Category	NSF Funded Man-Months Acad. Sum.	Proposed NSF
A. SALARIES AND WAGES		
1. Principal Investigator: full time for 2 months @ 2/9ths of academic year salary per month	2	\$ 2,880
2. Other Personnel (Non-Faculty)		
a. Graduate Student (Res. Ass't.):		
1. \$3,500 per academic year (student will have to pay tuition of approx. \$1,400 per academic year)	9	\$ 3,500
2. \$500 per month in summer	2	\$ 1,000
b. Secretarial - Clerical		
(One day per week for 20 weeks)		\$ 400
B. FRINGE BENEFITS		
15% of A 1 and 10% of A 2b		\$ 472
Total Salaries, Wages and Fringe Benefits (A + B)		<u>\$ 8,252</u>
C. PERMANENT EQUIPMENT		
1. Nuclide Cathodoluminoscope, Model ELM-2A including focusing system, two-stage mechanical vacuum pump, and spare parts kit (10% discount)		\$ 3,060
2. One each of Sr- and Ca- tube for Unicam SP-90 Atomic Absorption Spectrophotometer		\$ 250
3. One specimen storage cabinet with about 10 drawers (Lane #301 or equivalent) necessary to house new specimens		\$ 500
Total Permanent Equipment		<u>\$ 3,810</u>

Budget Category	NSF Funded Man-Months Acad. Sum.	Proposed NSF
D. EXPENDABLE SUPPLIES AND EQUIPMENT		
1. 30 polished-thin sections: \$6.50/section		\$ 195
2. 100 thin sections: \$3.00/section		\$ 300
3. 20 polished sections for electron microprobe analysis: \$5.00/section		\$ 100
4. Chemicals for heavy liquid concentration, dissolving samples, ion-exchange column, etc.		\$ 100
5. Field supplies, e.g., sample bags, wire brushes, buckets, miner's rubber boots and gloves, ruck-sack for carrying samples, etc.		\$ 100
6. Photographic Supplies		
a. 10 of 36 exposure black and white film and print paper		\$ 35
b. 10 of 36 exposure color film including processing		\$ 65
c. 10 cassetts (8 exposures each) of color and black-white Polaroid film for electron probe work		\$ 30
7. Tight seal vials (150) and storage boxes for concentrated samples		\$ 35
8. Agate mortar and pestle		\$ 45
9. Power grinder kit for drilling out small grains from a rock slab, thin- or polished- sections		\$ 88
10. Miscellaneous supplies		\$ 50
Total Expendable Supplies and Equipment		<u>\$ 1,143</u>
E. TRAVEL		
Domestic travel to one scientific meeting per year for one person		<u>\$ 200</u>

Budget Category	NSF Funded Man-Months Acad. Sum.	Proposed NSF
F. PUBLICATION COSTS		none
G. OTHER DIRECT COSTS		
1. Field Expenses		
a. Transportation: travel expenses for two persons to and from field area and within field area (5,000 miles at 10¢/mile; one-way distance Boston - Cave-In-Rock, Ill. approx. 1,500 miles; one-way distance from town to the mine approx. 25 miles)		\$ 500
b. Room and Board Allowances: Per diem @ \$8/day per man for two men for 60 days		\$ 960
c. Transportation of samples to Boston; Renting of an U-Haul tow trailer for 3 days		\$ 45
2. Use of electron microprobe (20 hrs. at \$20/hr.)		\$ 400
3. Equipment Service		\$ 80
Total Other Direct Costs		<u>\$ 1,985</u>
H. TOTAL DIRECT COSTS (A through G)		<u>\$15,390</u>
I. INDIRECT COSTS		<u>\$ 3,648</u>
\$3,880 @ 30.09% (off-campus) \$1,168		
\$3,900 @ 63.60% (on-campus) \$2,480		
J. TOTAL COSTS (H and I) FOR FIRST YEAR		<u><u>\$19,038</u></u>

Year Beginning February, 1974

Budget Category	NSF Funded Man-Months Acad. Sum.	Proposed NSF
A. SALARIES AND WAGES		
1. Principal Investigator: Full time for 2 months with projected 6% increase over 1973 salary	2	\$ 3,050
2. Other Personnel (Non-Faculty)		
a. Graduate Student (Res. Ass't.):		
1. \$3,500 per academic year (student will have to pay tuition of approx. \$1,000 per academic year)	9	\$ 3,500
2. \$500 per month in summer	2	\$ 1,000
b. Secretarial - Clerical		
(One day per week for 20 weeks)		\$ 400
B. FRINGE BENEFITS		
15% of A 1 and 10% of A 2b		\$ 498
Total Salaries, Wages and Fringe Benefits (A + B)		<u>\$ 8,448</u>
C. PERMANENT EQUIPMENT		
One specimen storage cabinet with about 10 drawers (Lane #301 or equivalent) necessary to house new specimens		\$ 500
Total Permanent Equipment		<u>\$ 500</u>
D. EXPENDABLE SUPPLIES AND EQUIPMENT		
1. 30 polished-thin sections: \$6.50/section		\$ 195
2. 100 thin-sections: \$3.00/section		\$ 300
3. 20 polished-sections for electron microprobe analysis: \$5.00/section		\$ 100
4. Chemicals for heavy liquid concentration, dissolving samples, ion-exchange column, etc.		\$ 100

Budget Category	NSF Funded Man-Months Acad. Sum.	Proposed NSF
5. Field supplies, e.g., sample bags, wire brushes, gloves, etc.		\$ 50
6. Photographic Supplies		
a. 10 of 36 exposure black and white film and print paper		\$ 35
b. 10 of 36 exposure color film including processing		\$ 65
c. 10 cassettes (8 exposures each) of color and black-white Polaroid film for electron probe work		\$ 30
7. Tight seal vials (150) and storage boxes		\$ 35
8. Miscellaneous supplies		\$ 50
Total Expendable Supplies and Equipment		<u>\$ 960</u>
E. TRAVEL		
Domestic travel to one scientific meeting per year for one person		<u>\$ 200</u>
F. PUBLICATION COSTS		<u>\$ 200</u>
G. OTHER DIRECT COSTS		
1. Field Expenses		
a. Transportation: Travel expenses for two persons to and from field area and within field area (5,000 miles at 10¢/mile; one-way distance Boston - Cave-In-Rock, Ill. approx. 1,500 miles; one-way distance from town to the mine approx. 25 miles)		\$ 500
b. Room and Board Allowances: Per diem @ \$8/day per person for two persons for 30 days		\$ 480
c. Transportation of samples to Boston; Renting of an U-Haul tow trailer for 3 days		\$ 45

Budget Category	NSF Funded Man-Months Acad. Sum.	Proposed NSF
2. Use of electron microprobe (20 hrs. at \$20/hr.)		\$ 400
3. Equipment Service		80
Total Other Direct Costs		<u>\$ 1,505</u>
H. TOTAL DIRECT COSTS (A through G)		<u>\$11,813</u>
I. INDIRECT COSTS		
\$4,050 @ 30.09% (off-campus)	\$1,219	
\$3,900 @ 63.60% (on-campus)	\$2,480	
J. TOTAL COSTS (H and I) FOR SECOND YEAR		<u><u>\$15,512</u></u>
TOTAL COST OF THE PROJECT		<u><u>\$34,550</u></u>

The Principal Investigator will devote approximately 20% of his time during the academic year to the proposed project. The estimated value of Boston University's contribution for this academic year effort (including fringe benefits and overhead) during two years is \$9,532.

CURRENT SUPPORT AND PENDING APPLICATION

Research support of about \$2,000 is presently being received from the Graduate School of Boston University to initiate the proposed project. No proposals are being considered by, or will be submitted to, other organization.

APPENDIX I: DESCRIPTION OF THE HILL AND OXFORD MINES

Hill Mine (Location: E 1/4 of Sec. 23, T. 11 S., R. 9 E.)

The main ore horizon of the Hill Mine occurs along the upper part of the Joppa Limestone Member and below the base of the Rosiclare Sandstone Member. A few ore veinlets and breccia filled ore material, however, occur locally within the lower part of the Rosiclare Member. A subordinate ore accumulation occurs also along the upper part of the Fredonia Member.

The ore body occurs in a narrow inclined valley or in channels. When ore is not found, these valleys and channels are filled with turbidites, calcareous shales, and breccias of primary and secondary origin. The thickness of the ore is variable, ranging up to 1 m. Ore minerals consist mainly of fluorite and subordinately of barite. The latter is found more abundantly, though sporadic in its distribution, than in the Deardorff Mine. Sphalerite and galena are found less abundantly than those of the Deardorff. They usually occur in solution vugs, cavities, and cross-cutting fractures.

On a hundred-meter scale, the ore body is congruent to the host limestone. On a smaller scale, however, incongruency and cross-cutting features are more abundant here than in the ore layers of the Deardorff Mine.

Ore layers are usually found inside or near the primary and diagenetic sedimentary structures, such as erosion channels, slumps, vugs, stylolites and other solution structures. The ore layers tend to be thicker under the thick shale unit than under the shale-barren zone, which was subjected to an active submarine erosion during and shortly after the shale deposition.

Fredonia working horizon of the Hill Mine: Ore layers occur in the upper part of the Fredonia Limestone Member. Their thickness may reach up to 1 m and the layers lie more or less horizontal to the bedding plane. Contrary to the Deardorff Mine, the Spar Mountain Sandstone Member occurs throughout the ceiling of the mine workings. Vug fillings are also numerous. At few places, the lower-most part of the Spar Mountain Sandstone Member has been broken and brecciated. The breccia matrix consists dominantly of fluorite. Numerous horizontal stylolitic seams occur in the ore layers and in the oolitic host limestone. Galena and sphalerite are very common, whereas along the upper Joppa workings they are rarer.

Galena and sphalerite are more common along the stratigraphically lowest Fredonia working horizons in the district, whereas barites predominate in the upper workings, i.e., the Joppa and the Downeys Bluff horizons.

Oxford Mine (Location: NW 1/4 of Sec. 25, T. 11 S., R. 9 E.)

Two stratigraphic horizons are productive; the upper part of the Joppa Limestone Member and the upper part of the Downeys Bluff Limestone Formation. The following descriptions are mainly made for the latter horizon which is the main ore horizon.

The main ore body occurs as a narrow and long blanket which is 30-50 m wide, up to 2-3 m thick and about 500 m long. The ore layers pinch out laterally away from the N 50° E long axis of the blanket.

Three normal faults with a displacement of locally up to 4 m run parallel to and along the northwestern part of the ore blanket. The dips of the faults range from 70° NE to 80° SW. One of the faults with a displacement of about 4 m and with a strike and dip of 50° NE and 80° SW continues downwards the Joppa working horizon which lies about 37 m below. Along this fault at both horizons, massive yellow fluorite and barite are filled with a thickness of 0.5 - 1 m. Ores filled into this fault are thought to be a later mineralization, different in time from the blanket mineralization.

The ore minerals consist largely of barite and fluorite. Sphalerite is rare and galena almost absent.

A number of ferroan dolomite veinlets occur; gravity and compaction features associated with them suggest a diagenetic origin of them.

Sedimentary features associated with barite indicate that barite was deposited rather late during mineralization.

APPENDIX II: SUMMARY OF PARAGENETIC SEQUENCE; DEARDORFF, HILL AND OXFORD MINES

a. Depositional stage

1. Formation and deposition of allochemical grains, i.e., oolites, onkoids and bioclasts under well-aerated shallow marine environment above wave base. Locally, micrite deposition under low energy environment.

2. Locally, formation of primary channels and slumps.
3. Formation of intraclasts through mechanical erosion by wave action.
4. Locally and occasionally, deposition of detrital well-rounded quartz sands and clays which were transported by streams from N-NE.

b. Early cementation stage

1. Cementation by radiaxial aragonite, subsequently transforming to 'dog-tooth type' calcite later, on the free surfaces of oolites, onkoids and bioclasts.

2. Some degree of recrystallization, including inversion of aragonite to calcite (liberation of Sr in pore fluids) of the micritic portions of oolites and bioclasts (micrite enlargement).

3. Possible formation of micrite envelopes.

4. Initiation of rim cementation and replacement rim on bioclastic monocrystalline calcite.

5. Selective replacement of micritic oolites by doubly terminated euhedral quartz.

6. Replacement of micritic oolites by chalcedonic quartz which is first followed by the deposition of clear euhedral quartz and lastly by the deposition of drusy fluorite in the remaining pore spaces. The time of deposition of this fluorite may correspond to the Intermediate cementation stage.

7. Locally formation of framboidal and microscopic pyrite and bravoite and rarely chalcopyrite.

8. Replacement of micritic oolites by early generation sphalerite.

9. Possible formation of fine grained fluorite which subsequently has recrystallized during the later stages.

10. Possible development of syneresis tension fractures in chert.

11. Locally, intraformational brecciation.

12. Initiation of the formation of moldic pores through dissolution of bioclasts and oolites in dolomicrites and dolomicrosparites.

13. Initiation of pressure-solution and stylolitization.

c. Intermediate cementation stage

1. Cementation of oolites and bioclasts by drusy mosaic calcite is active.
2. Cementation by dolomite and dolomitization in certain portions.
3. Recrystallization of micritic portions continue.
4. Locally desilicification
5. Cementation and replacement of calcite by fluorite accompanying silica deposition in ore horizons. Recrystallization of carbonates predominate.
6. Locally cementation of pores by strontianite.
7. Possible formation of geodes and vugs.
8. Stylolitization active through dissolution and overburden pressure; accumulation of various ore minerals within and along the stylolitic solution seams.

d. Late cementation stage (in part epigenetic stage)

1. Later and final stage of drusy mosaic calcite, ferroan calcite and in part dolomite cementation.
2. Main mineralization which accompanies extensive recrystallization of the host rocks (aggrading coalescive neomorphism). Formation of sphalerite (earlier), dolomite, galena + tennantite, quartz and fluorite (later). Replacement of sphalerite by quartz is characteristic. Locally quartz may form before sphalerite.
3. Formation of idiotopic poikilotopic dolomite in a matrix of fluorite.
4. Depositions (at least 2 generations) of colloform barite layers. Locally, dissolution of barite and subsequent deposition of witherite and strontianite.
5. Pressure-solution between grains and stylolitization less active in host carbonate rocks and end concordantly with the complete cementation of pore space. Stylolitization, however, may be active within zones of mineralization where dissolution of carbonates predominant.

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