GYPSUM AND ANHYDRITE DEPOSITS IN SOUTHWESTERN INDIANA

by

DUNCAN J. McGREGOR

Indiana Department of Conservation
GEOLOGICAL SURVEY
Report of Progress No. 8

1954

STATE OF INDIANA
George N. Craig, Governor

DEPARTMENT OF CONSERVATION
Harley G. Hook, Director

GEOLOGICAL SURVEY
Charles F. Deiss, State Geologist
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GYPSUM AND ANHYDRITE DEPOSITS
IN SOUTHWESTERN INDIANA

By Duncan J. McGregor

ABSTRACT

This report discusses the production and uses of gypsum and the types of gypsum and anhydrite deposits, their physical and chemical properties, geologic association, and theories of origin.

Subsurface studies in southwestern Indiana have revealed rather extensive gypsum deposits in the lower part of the St. Louis limestone. Stratigraphic analysis of this evaporite unit indicates that gypsum ($CaSO_4 . 2H_2O$) and anhydrite ($CaSO_4$) accumulated in small basins within larger basins (intrasilled basins). The isopach map (pl. 1) suggests that three major intrasilled basins exist in southwestern Indiana and that these basins are aligned in a northwest- southeast direction that corresponds to the trend of the rock formations. The isopleth map (pl. 2) indicates that the maximum accumulation of the evaporites corresponds to the geographic locations of the intrasilled basins.

The broad up-and-down movement of the earth's crust (epeirogenic movement) caused the formation of a submarine topography which affects evaporitic environments. Epeirogenic movement, which probably was cyclic, is reflected in a depositional pattern that changes from normal open-sea circulation to a restricted-sea environment and then returns to normal open-sea circulation. The evaporite cycle of marine, [1] penesaline, [2] and marine results from both tectonic and environmental causes.

INTRODUCTION

Purpose of investigation

This investigation was undertaken to make known the salient features of evaporites (gypsum and anhydrite) in southwestern Indiana and to determine their origin, geologic occurrence, uses, and relationship to associated rock strata.

A detailed study of evaporites in Indiana has never been undertaken. In fact, it was not known until recently that relatively thick beds existed in the state. Evaporites, however, are not new among the minerals f ound in Indiana; they have been observed in well cuttings

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[1] Fossiliferous, fragmental limestone.

[2] Limestone, dolomitic limestone, and gypsum and anhydrite.

and as nodular masses and thin beds in outcrops. Logan (1922, P.1052) reported that a thin bed of gypsum (selenite) crops out between the Beaver Bend limestone and Sample sandstone in a railroad cut east of Huron, Lawrence County. Gypsum also occurs commonly as nodular masses in the Harrodsburg and St. Louis limestones and in many places forms a conspicuous part of their lithology. Moreover, as stated above, subsurface studies in southwestern Indiana have revealed rather extensive gypsum deposits in the lower part of the St. Louis limestone.

Source of information

Data for this investigation were obtained from drill cuttings, sample logs, electric logs, and drillers' logs, all of which are on open file in the Petroleum Section, Indiana Geological Survey, Bloomington, Ind. Detailed studies of 117 sections were made. As the information in some areas is scanty, only a generalized picture can be presented. This paper attempts to describe the tectonic and environmental setting of the evaporites by employing conventional means of stratigraphic analysis (Krumbein, 1948, pp. 1909-1923). The information contained herein is inadequate to indicate specific deposits but should serve to stimulate commercial production of gypsum.

THE GYPSUM INDUSTRY

Production

The demand for gypsum and gypsum products has increased in recent years. Gypsum produced in the United States for the first half of 1953 amounted to 3,750,257 tons (Gutschick, 1954, p. 126). Most gypsum products were produced and sold in larger quantities during the first half of 1953 than in the corresponding period of 1952. If present trends are indicative of the future, the gypsum industry will continue to operate at a high level of production. At present Michigan leads in gypsum production, followed closely by California and New York.

Uses of gypsum

Raw or uncalcined gypsum is used in agriculture as a fertilizer. When gypsum is added to the soil, it reacts chemically with other compounds. This chemical reaction provides valuable plant foods, such as sulphur trioxide, which is required by most cereal and legume

plants. The reaction of sulphate on the silicates, such as feldspars, probably releases potassium for plant assimilation. Although most soils are reported to contain much potassium, it is commonly fixed in the silicates.

Uncalcined or raw gypsum also is used in making plaster of paris or cement plaster. This product is obtained by subjecting raw gypsum to low heat, which removes most of the chemically combined water. Plaster of paris thus will set or harden when mixed with water.

Much of the world's output of calcined gypsum is used by the building industry. Manufactured products include: (1) hardwall plaster, calcined gypsum to which fiber material and retarder have been added; (2) sand gauging and many other building plasters; (3) wallboard, lath, and sheathing board; (4) various tiles; and (5) many special plasters of extremely high quality, such as those used by the plate glass and terra-cotta industries and by orthopedists and dentists and those used for pottery, statuary, and industrial casing and molding.

Economics

As gypsum is a low-priced commodity and cannot absorb high transportation costs, sales are restricted geographically. The average price of gypsum mined in 1952 was $2.72 per ton; the average price of finished products ranged from $3.43 to $78. 54 per ton (North and Jensen, 1953, pp. 1 and 6).

Before exploiting a gypsum deposit one should consider: (1) the extent and purity of the deposit; (2) the cost of mining and transporting; (3) current production in the area; and (4) the potential market and its extent. One should realize that the eventual utilization of a deposit is more dependent upon economic than upon technical factors.

PHYSICAL AND CHEMICAL PROPERTIES OF GYPSUM

Gypsum ($CaSO_4$- $2H_2O$) and anhydrite ($CaSO_4$) are the two calcium sulphate minerals occurring in nature. Gypsum is the hydrated form of calcium sulphate in which the water and calcium sulphate are intimately bound together. It is the combined water that makes gypsum an important commercial mineral.

Pure gypsum contains 32. 5 percent CaO, 46. 6 percent SO_3, and 29. 9 percent H_2O. The pure mineral is commonly white, but it may be various shades of gray, brown, red, or pink, depending upon the nature of the impurities, Gypsum has a hardness of 2 (Moh's scale) and can be scratched easily with the fingernail. As its specific gravity ranges from 2. 32 to 2.40, gypsum is softer and lighter than pure limestone or calcite, which has a hardness of 3 and a specific gravity of

2.72.

Gypsum is slightly soluble in pure water; one part gypsum dissolves in 415 parts water at 0E C. Alkaline chlorides increase its solubility. Gypsum crystallizes in the monoclinic system and forms tabular crystals that exhibit perfect cleavage in one direction. The thin cleavage sheets are flexible but not elastic and, if bent sharply, will break in a diagonal direction. Gypsum crystals commonly form to so-called "arrowhead" or "swallowtail" twins.

Several varieties of gypsum are recognized: selenite, the colorless and commonly transparent form; satin spar, the fibrous form; rock gypsum, the massive form; alabaster, the massive form used for ornaments; and gypsite, the impure earthy form.

PHYSICAL AND CHEMICAL PROPERTIES OF ANHYDRITE

Anhydrite ($CaSO_4$) contains 41. 2 percent CaO and 58. 8 percent SO_3. Because anhydrite is without water of crystallization, it has little or no industrial value and where associated with gypsum is referred to as an impurity. Pure anhydrite is commonly white but may be tinged a faint gray, blue, or red. Anhydrite is slightly harder and heavier than gypsum and pure limestone and crystallizes in the orthorhombic system. It cleaves in three directions at right angles to each other (pseudocubic) and is less soluble in pure water than gypsum; one part anhydrite dissolves in 525 parts water at 0E C. Alkaline chlorides also increase its solubility. In thin sections anhydrite may be distinguished from gypsum and calcite by its pseudocubic cleavage and higher birefringence.

TYPES OF -GYPSUM DEPOSITS

Bedded deposits

Bedded deposits are the most important commercial sources of gypsum. In bedded deposits massive gypsum, together with limestone, dolomite, shale, and sandstone, occurs in stratified sequence. The gypsum beds are likely to be persistent and commonly conform to associated rocks in their structure. In New York, Michigan, Kansas, Ohio, and Iowa, gypsum and associated rock strata are nearly horizontal.

Bedded gypsum deposits are fairly uniform physically and chemically. In those regions where gypsum is mined, any particular stratum within the limits of the mine workings has an almost constant gypsum content. Anhydrite is the main element of uncertainty, and this mineral is   apt   to   increase   with   depth.   In   New   York   anhydrite   is

encountered at a depth of about 150feet, whereas in Michigan it occurs at an approximate depth of 450 feet. Thus, the upper limit of anhydrite occurrence must be determined for any area. The most extensive bedded gypsum deposits in the United States are in the Silurian of New York, the Mississippian of Michigan, and the Permian of Kansas, New Mexico, and Texas.

Surface deposits

In dry or semiarid regions circulating ground waters may come in contact with buried gypsum beds. The groundwater dissolves some of the gypsum and carries it in solution to the surface, where it is reprecipitated to form gypsum and anhydrite. These minerals also may be formed in shallow ponds or lakes into which ground waters that have been in contact with gypsum discharge and evaporate. Such surface deposits are called gypsite and are mixtures of gypsum or anhydrite with clay, carbonates, sand, and organic matter. Gypsite maybe found in superficial deposits mostly in the western and southwestern parts of the United States. Gypsite deposits are as much as 30 or 40 feet thick and may cover areas ranging from a few acres to several square miles. Gypsite is used extensively for wall plasters and agricultural purposes, but it is not suitable for high-grade gypsum products. Gypsum sand occurs in the southwestern regions, notably New Mexico, where it lies in dunes that shift about in the wind.

Vein deposits

Small fissures and cavities commonly are associated with gypsum beds; these maybe filled with gypsum in the form of selenite or satin spar, precipitated from ground water. In many places large crystals develop because of slow evaporation. Most vein deposits have little commercial value.

GEOLOGIC ASSOCIATION OF GYPSUM AND ANHYDRITE

Gypsum almost universally is associated with anhydrite and represents the stable phase of calcium sulphate at the surface, whereas anhydrite represents the stable phase at depth.

Gypsum and anhydrite deposits commonly are interbedded with, or rest upon, limestone or dolomite but also are associated with salt and shale, which in many places are red. In some areas a continuous deposit of gypsum and anhydrite may occur, but in most places gypsum and anhydrite are interbedded with "red beds, limestone, dolo-

mite, or salt.

The association of gypsum and anhydrite with other sediments indicates that the normal sequence of deposition was interrupted. Several factors may interfere with the natural evaporation of seawater For example, the influx of normal seawater through enlarged channels or during a period of high tides will stop precipitation at any intermediate stage. Likewise, clastic sediments, sands and muds, may be carried by streams flowing into a restricted sea in which one would expect a wholly chemical sequence of deposition to take place.

The distribution of evaporites maybe affected by wave and current action. The reworking of gypsum and anhydrite particles in concentrated brines may result in selective segregation and movement of the particles toward the basin. Thus, abnormally thick deposits of gypsum or anhydrite may accumulate in the center of a basin.

Some deposits of gypsum and anhydrite and the associated sediments may contain laminae of brown material, which is probably bituminous matter. The rocks even may have a fetid odor. Organisms, swept into a restricted sea by inflowing waters, are ultimately destroyed by the abnormally high salinity. Only those organisms that can tolerate a saline environment survive. Therefore, biological factors contribute few impurities to gypsum or anhydrite deposits.

ORIGIN OF GYPSUM AND ANHYDRITE

The origin of gypsum and anhydrite involves two questions: (1) Was calcium sulphate deposited originally as anhydrite or as gypsum? and (2) What conditions led to the concentration of calcium sulphate?

The association of calcium sulphate with other evaporites affords evidence for believing that calcium sulphate may be precipitated from the evaporation of seawater. Usiglio's investigations of the evaporation of sea water (Clarke, 1924, pp. 219-220) show that limestone and iron oxide are precipitated when the original volume of seawater is reduced to about one-half; gypsum and a small amount of limestone are formed when the volume is reduced to one - fifth the original volume; sodium chloride, some gypsum, and traces of limestone are deposited at one-tenth the original volume; and after still further reduction the bitterns (sulphates and chlorides of magnesium, sodium bromides, and potassium chlorides) are formed. This sequence of salt formation would be rare indeed, however, because evaporation seldom continues until the most soluble salts are precipitated. Moreover, the sequence given above would not necessarily apply to other saline waters that have different proportions of the same salts, as both the sequence of deposition and the composition of the precipitates are determined by the concentration of salt in sea water and by the temperature of the water.

Sverdrup, Johnson, and Fleming (1942, pp. 165-168) pointed out that the constancy of composition of seawater is of first importance because it is the basis of chlorinity, salinity, and density relationships and is the means by which concentration of all major constituents maybe estimated when the concentration of any one element is known. In all sea waters, regardless of the absolute concentration of total solids, the relative proportions of the various "salt" ions are virtually constant, and the total amount of salts dissolved in sea water can be determined by the measurement of only one constituent. The composition of normal sea water is about 3. 5 percent dissolved material; four-fifths of this amount is sodium chloride. The composition of normal sea water with a salinity of 34. 3 parts per thousand is shown in the following table.

Composition of normal sea water
(after Kuenen, 1950, p. 15)

Ions in solution	Grams per kilogram 0/00	Grams of salts crystallizing from 1 kg	
Cl^-	18.98	NaCl	27.21
Br^-	0.065	$MgCl_2$	3.81
$SO_4^=$	2.65	$MgSO_4$	1.66
HCO_3^-	0.14	$CaSO_4$	1.26
Mg^{++}	1.27	K_2SO_4	0.86
Ca^{++}	0.40	$CaCO_3$	0.12
K^+	0.38	$MgBr_2$	0.08
Na^+	10.56		

Posnjak (1938, pp. 247-272) restudied the relationship between gypsum and anhydrite through laboratory experiments and found that gypsum is deposited from saturated calcium sulphate solutions at temperatures below 42E C. and that anhydrite is deposited when the temperature is above 42E C. Posnjak concluded that gypsum is precipitated at a temperature of 30E C. and a salinity ranging from 3. 35 to 4. 8 times normal sea-water concentration; anhydrite is precipitated when the salinity reaches 4. 8 times normal. Furthermore, he found that about half of all calcium sulphate present is precipitated as gypsum before anhydrite begins to crystallize. Anhydrite maybe directly precipitated, however, when the volume is reduced to about one -fifth the original volume. Thus, Posnjak's experimental evidence means that gypsum always is deposited first at temperatures of evaporation in marine basins. If marine beds of anhydrite are found, one concludes either that the anhydrite was formed from the earlier deposits of gypsum or that gypsum was deposited at a temperature above

42E C. The latter explanation, according to Posnjak's studies, is most unlikely.

Geologic evidence (Newland, 1929; Muir, 1934; McGregor, 1948), however, indicates that the original material of most gypsum beds probably was anhydrite. Gypsum that grades into anhydrite at depth, gypsum veins and irregular penetrations of gypsum in anhydrite, and relic anhydrite in gypsum all support this evidence.

Pettijohn (1949, p. 360) showed that precipitation of the salt in a 1,000-foot column of water would result in 0. 4 foot of calcium sulphate, 11. 6 feet of sodium chloride, and 3 feet7 of potassium- and magnesium -bearing salts. Thus, to yield 300 feet of calcium sulphate, a depth of 750, 000 feet, or 142 miles, of sea water would have to be evaporated. As evaporation of this amount of water is fantastic, sea water must have been added from time to time to the basin of deposition during evaporation, and the waters containing concentrations of calcium sulphate must have been confined to the intrasilled basins.

As the water in most closed basins is relatively shallow, [3] evaporation in these basins should yield a layer of common salt above the calcium sulphate. Therefore, where calcium sulphate is found with no overlying salt, conditions at the time of deposition must have been unusual. Likewise, in areas where salt is present but gypsum is not, the normal sequence of deposition must have been interrupted. Thus, any theory for the origin of thick calcium sulphate beds must account for: (1) the means by which large volumes of sea water were supplied to the evaporating basin; (2) the cessation of deposition before sodium chloride or bittern salts were deposited; and (3) the alternating deposits of sodium chloride and calcium sulphate.

Various theories have been advanced to account for the gypsum deposits found throughout the world. Ochsenius (Newland, 1929, p. 57) proposed that the evaporation of sea water took place in basins which were partially cut off from the sea. These basins received additional water from adjacent seas as evaporation progressed. A more or less continuous "salt pan" resulted, and rather shallow basins sufficed for the accumulation of thick beds of limestone, salt, or gypsum. Branson (1915, pp. 231-242), in presenting a modification of Ochsenius' theory, assumed that subbasins or lagoons separated by low barriers lay within the basins. Water entered the outer basins and overflowed into the inner basins, carrying with it the concentrated brines. Consequently, gypsum was deposited in the outer basins, and halite in the inner basins.

King (1947, pp. 470-477) in his investigation of the Castile anhydrite in the Delaware Basin in West Texas and southeastern New

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[3]The epineritic zone of Scott (1940, pp. 301-302) that ranges from less than 1 fathom (6 feet) up to 20 fathoms (120 feet).

Mexico concluded that anhydrite had been deposited in a semi-isolated sea into which normal seawater had been added through a restricted channel. The precipitate from the concentrated brines tended to sink to the bottom of the basin and was, in part, returned to the open sea by a kind of reflux action. Anhydrite rather than gypsum was deposited finally because of the salinity of the sea water. King showed that even though gypsum was deposited initially, the anhydrite stage of precipitation was reached in about 1/1,000 part of Castile time if one assumes that the temperature of the seawater was 30E C Furthermore, King showed that the ratio of influx to reflux was about 10 to 1. This ratio would account for anhydrite precipitation with little or no sodium chloride and also would permit the most soluble salts to be carried out of the basin into the sea.

Scruton (1953, pp. 2498-2512), in discussing the deposition of evaporites, pointed out that a characteristic circulation pattern exists in estuaries and other restricted arms of the sea. In response to hydrostatic head, surface currents flow from areas of low salinity[4] to those of high salinity; these currents are accompanied by deeper currents flowing from areas of high to areas of low salinity. Salts are deposited in those restricted estuaries or basins where evaporation exceeds precipitation and runoff. [5]

A strong salinity gradient exists where high concentrations of salts are found. This gradient causes lateral segregation of various salts during precipitation. Those salts which have not been precipitated (the most soluble salts) are returned to the sea by escaping deep seated currents. The migration of the horizontal salinity gradient along the longitudinal axis of the restricted estuary results from fluctuations in equilibrium caused principally by changes either in the amount of evaporation or in the extent of channel closure. The different salinity ranges at which precipitation of various salts takes place produce horizontally segregated, pure evaporite deposits.

As migration of the horizontal salinity gradient also causes vertical differentiation of salts, one can predict vertical sequences of beds that agree with known natural sequences of rocks.

The oxidation of pyrite, especially that found in black shales, commonly results in the formation of acid sulphate waters. The sulphate-bearing waters react with l i m e s t o n e   a n d   m a y   c o n v e r t   m u c h   o f

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[4]Changes in salinity are caused by (1) precipitation, (2) channel restriction, and (3) variations in temperature, sealevel, or wind stress.

[5]Restrictions of the estuaries or basins are: (1) dynamic (caused by the hydrostatic head and by frictional stresses between surface currents and the oppositely directed bottom currents on the channel floor) and (2) static (produced by topographic confinement).

it to gypsum. Most commercial gypsum deposits, however, do not seem to be of this origin.

STRATIGRAPHIC ANALYSIS OF EVAPORITES

Stratigraphy of evaporite unit and adjacent rock strata

The stratigraphy of the lower part of the St. Louis limestone (evaporite unit) and of the underlying and overlying rocks is shown in figure 1. To minimize errors that might be introduced into the analysis because of erosion, the evaporite unit was analyzed only in places where it is overlain by younger deposits (the upper part of the St. Louis limestone). Stratigraphic details are discussed briefly in order to point out significant criteria used in placing the upper and lower boundaries of the evaporite unit.

The formations studied in this analysis are the Salem and St. Louis limestones, both of Meramecian age. The evaporite unit includes those rocks that lie between the top of the Salem limestone and a marked lithologic break that occurs about midway in the St. Louis limestone.

The Salem limestone (building stone zone) is commonly light bluish gray to gray, even-grained, granular, and porous. It commonly contains many small fossils and fossil fragments (Endothyra baileyi and fenestelloid bryozoans). Locally thin brown calcareous shale is at the top. In some areas drab-brown, silty, argillaceous dolomitic rock ("bastard stone" of the quarry industry) forms an impure zone that is found most commonly above the building stone zone.

In many places the lower part of the St. Louis limestone is blue gray, fine-grained tolithographic, argillaceous, and locally dolomitic. Fossils are rare. Either gray and black shale or black shale is present locally. The evaporite beds (gypsum and anhydrite) are in this interval of the St. Louis limestone. The upper part of the St. Louis limestone may be grayish tan to brown, commonly denser, cherty, and dolomitic.

Evaporite unit

Definition of unit. --The base of the evaporite unit is marked by a lithologic change between the St. Louis limestone and the underlying Salem limestone. Where the St. Louis directly overlies the building stone zone of the Salem, the lithologic break is distinctive. The light-tan to gray, commonly fine, even-grained, porous Salem limestone that contains abundant microfossils (Endothyra baileyi and fenestelloid bryozoans) makes a   sharp   contrast   with   the   blue   -gray,
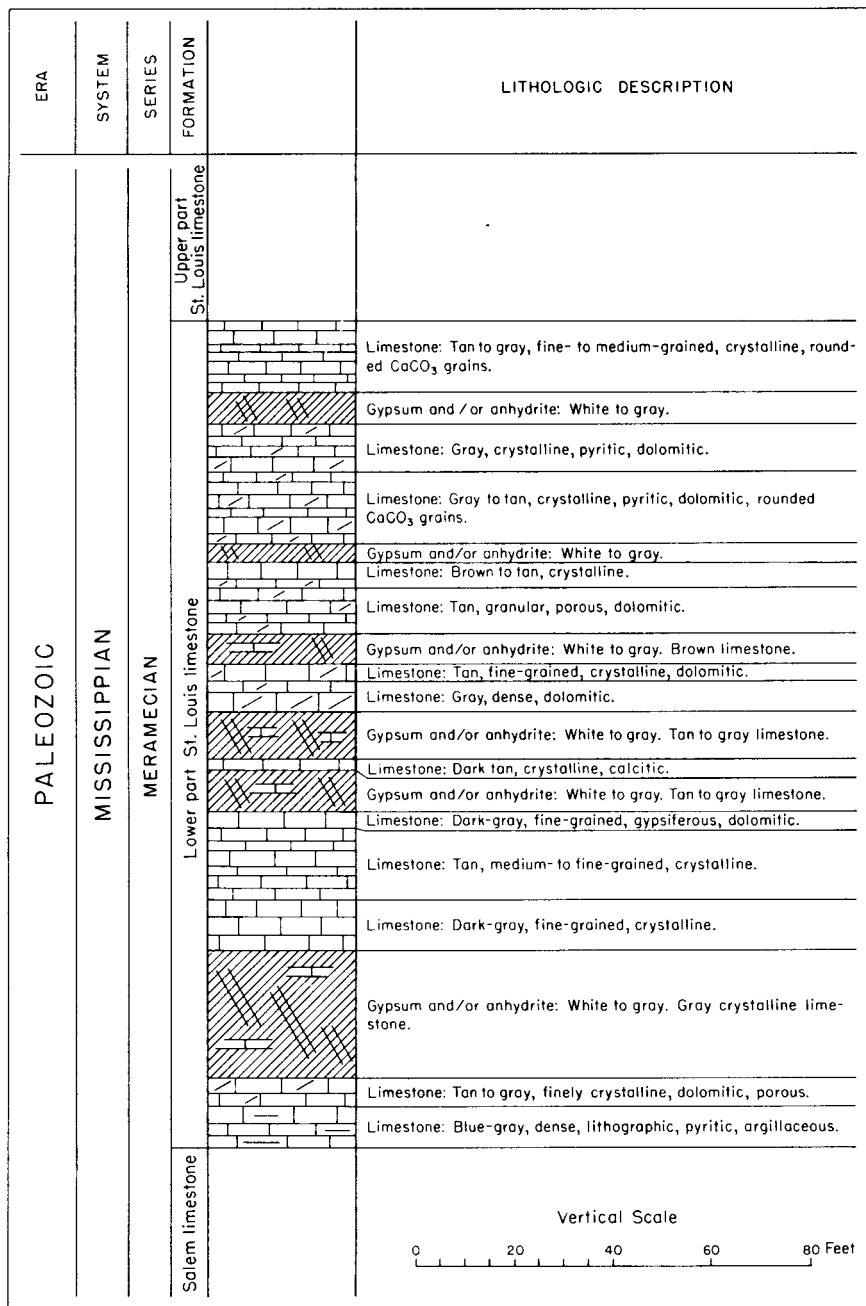
ERA	SYSTEM	SERIES	FORMATION		LITHOLOGIC DESCRIPTION
PALEOZOIC	MISSISSIPPIAN	MERAMECIAN	Upper part St. Louis limestone		
			Lower part St. Louis limestone		Limestone: Tan to gray, fine- to medium-grained, crystalline, rounded CaCO₃ grains.
					Gypsum and / or anhydrite: White to gray.
					Limestone: Gray, crystalline, pyritic, dolomitic.
					Limestone: Gray to tan, crystalline, pyritic, dolomitic, rounded CaCO₃ grains.
					Gypsum and/or anhydrite: White to gray.
					Limestone: Brown to tan, crystalline.
					Limestone: Tan, granular, porous, dolomitic.
					Gypsum and/or anhydrite: White to gray. Brown limestone.
					Limestone: Tan, fine-grained, crystalline, dolomitic.
					Limestone: Gray, dense, dolomitic.
					Gypsum and/or anhydrite: White to gray. Tan to gray limestone.
					Limestone: Dark tan, crystalline, calcitic.
					Gypsum and/or anhydrite: White to gray. Tan to gray limestone.
					Limestone: Dark-gray, fine-grained, gypsiferous, dolomitic.
					Limestone: Tan, medium- to fine-grained, crystalline.
					Limestone: Dark-gray, fine-grained, crystalline.
					Gypsum and/or anhydrite: White to gray. Gray crystalline limestone.
					Limestone: Tan to gray, finely crystalline, dolomitic, porous.
					Limestone: Blue-gray, dense, lithographic, pyritic, argillaceous.
			Salem limestone		

Vertical Scale

0   20   40   60   80 Feet

Figure I. *Generalized stratigraphic section of lower St. Louis limestone (evaporite unit) in southwestern Indiana.*

finely crystalline, commonly lithographic, nonfossiliferous St. Louis limestone. Where the St. Louis is in contact with the so-called "bastard stone" zone of the Salem, however, the line of demarcation is not so sharply defined. Nevertheless, by close observation one can differentiate fairly accurately the dark-blue-gray, finely granular to lithographic, argillaceous St. Louis limestone from the light-tan to gray, granular porous Salem limestone. The fossils, increasing in abundance downward in the section, also serve in distinguishing the St. Louis and Salem limestones.

The top of the evaporite unit is drawn on a lithologic break about midway in the St. Louis limestone. The break is characterized be low by a brown, fine- to medium-grained, crystalline limestone that in many places has rounded carbonate grains resembling oöliths; it is characterized above by a light-tan to brown, fine-grained, porous and commonly sugary dolomitic limestone. Chert fragments increase above the break and in most places are absent below it.

Thickness and lithofacies. --The isopach map (pl. 1) and isopleth map (pl. 2) show the relationship between the lateral variation in thickness of the evaporite unit and the localities of maximum evaporite occurrence.

The isopach pattern of the evaporite unit indicates that: (1) the unit thickens along the west edge of Indiana and apparently increases in thickness at a constant rate toward the center of the Illinois Basin; (2) the rate of thickening is constant for a short distance from the structural highs but decreases toward the center of each intrasilled basin; (3) the intrasilled basins are oriented along a line that corresponds to the formational strike;[6] (4) the isopach lines parallel the general trends of the Cincinnati Arch to the east and the Nashville dome to the south;[7] (5) the structural highs have random trends throughout the area; and (6) the evaporite unit thins in the direction of the Cincinnati Arch and the Nashville dome.

The isopleth map (pl. 2) shows that the sites of evaporite concentration are aligned in a northwest-southeast direction corresponding to the direction of the formational strike. A comparison of this map with the isopach map (pl. 1) reveals that the maximum thickness of evaporite deposits is in the intrasilled basins.

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[6]Three major intrasilled basins exist in southwestern Indiana: one in southwestern Orange County, northern Spencer County, Perry County, and southwestern Crawford County; one in central and western Martin County and Daviess County; and one in northern Greene County, southwestern Owen County, and southern Clay County.

[7]This fact indicates that the Arch existed as a positive feature during the deposition of the evaporite unit.

Tectonic and environmental interpretation. --The tectonic map of the Mississippian period (fig. 2) shows that the Ozark, Nashville, and Cincinnati Arches and the positive area that extends across northern Indiana were structural highs that encompassed the Illinois-Indiana-Kentucky Basin throughout late Mississippian and early Pennsylvanian time. The LaSalle anticline, which divides the Illinois-Indiana-Kentucky Basin into two parts, likewise was a positive feature, which, according to Eardley (1951, p. 18), first began to rise in late Mississippian time.

The tectonic map indicates that little epeirogenic movement took place during early and, middle Mississippian time. The isopach and
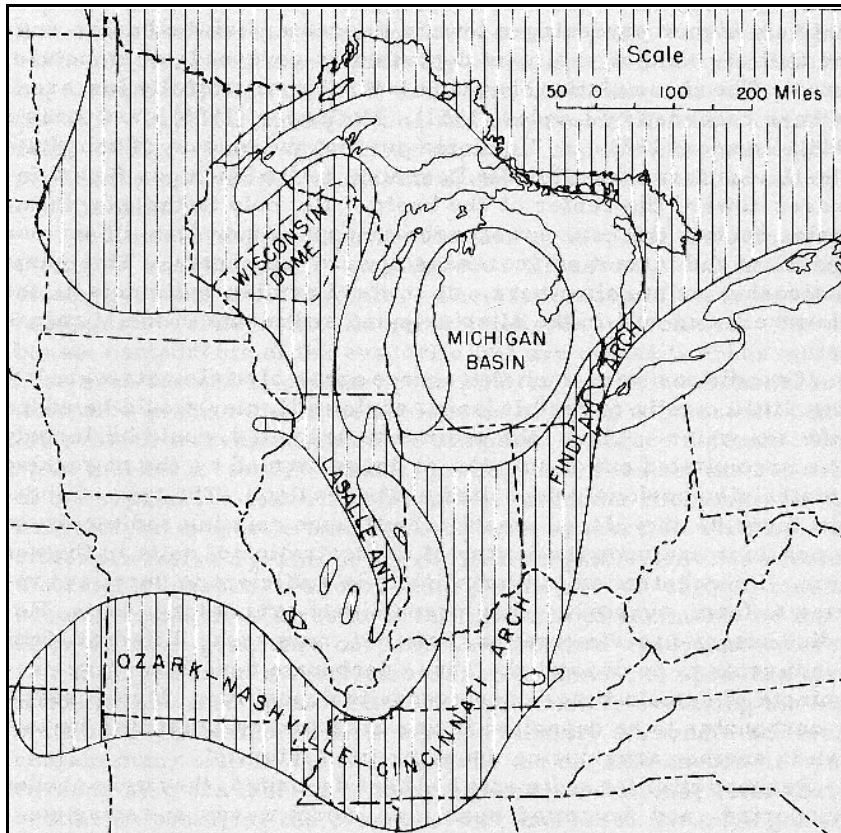
Figure 2. *Tectonic map of the Mississipian period showing structural high areas that were subject to erosion (after Edrdley, 1951).*

isopleth maps, however, indicate that epeirogenic movement, which resulted in the echelon northward-southward-trending structural highs (LaSalle anticline), began apparently in early Meramecian time, probably before or during deposition of the evaporite unit. Random orientation of the positive highs and cyclic deposition of the evaporites with other lithologic components substantiate the belief that epeirogenic movement in the basin and source areas took place periodically prior to or during the deposition of the evaporite unit. Epeirogenic movement caused sills to form within the basin, and thus the sea was segregated into isolated bodies of water, as is indicated by nonuniform carbonate and evaporite distribution and by concentration of carbonates and evaporites in small areas.

Thinner deposits and relatively low evaporite percentages at the outer edges of the silled basins as opposed to thicker deposits and relatively higher percentages toward the centers of the basins suggest that the kind of sediment deposited is governed by structural control. The accumulation of evaporites in the structurally low areas has been recorded by Landes (1951), McGregor (1953), and Adams (1944). Landes (1951, p. 7) pointed out that the amount of anhydrite in the Lucas formation (Middle Devonian) in the Michigan Basin increases toward the center of the basin. Not only is the anhydrite-bearing section thicker, but also the amount of anhydrite in any one interval of the formation increases toward the center. This same relationship exists elsewhere, as in the Permian sediments in the Delaware Basin and in the Mississippian sediments in the Michigan Basin.

If conditions were such that source areas of sediments were low lying, little clastic materials (sand, shale, silt, clay) would be added to the sea water. Thus, the sediments deposited would be largely those precipitated out of solution or those formed by the reworking of materials previously deposited on the sea floor. The type of sediment formed, therefore, would depend upon existing sediments on the sea floor and upon the degree of concentration of salts in the sea water. If concentration of marine salts is sufficient to permit evaporites to form, evaporites may predominate over a large area. Periodic changes in sedimentation, however, may cause different kinds of sediments to be deposited. Thus, carbonate deposition may predominate at certain times over evaporite deposition. It is possible for carbonates to be deposited in one area and evaporites to be laid down in another area during the same time interval.

Perhaps after the sediments had been deposited, they were eroded, transported, and deposited again, as storm waves and wave-generated currents picked up the finer components, transported them, and redeposited them farther toward the center of the basin. Normal processes of deposition again took place during quiet periods and then were interrupted by another storm wave. Little by little, as the basin

sank, sediments were buried deeply enough to prevent their being affected by wave-generated currents. This explanation of deposition may account for one type of lithology in one area and another type of lithology in another area, with gradations in lithology between.

Sediments of the evaporite unit and of the overlying and underlying strata indicate that the Indiana part of the Illinois Basin did not have continuous open-sea circulation. By observing these sediments, one can see that a change from open-sea circulation to a restricted sea environment and a return to open- sea circulation must have taken place.

Sediments below the evaporite unit are composed largely of microscopic fossil shells (Endothyra baileyi). These fossils, together with the structure and texture of the limestone, indicate a moderate depth of water, probably within the lower limit of the epineritic zone. Because the limestone contains little or no organic carbon or hydrocarbons, these sediments probably were laid down in a medium having a relatively high pH (7.8) and a high oxidation-reduction potential (Eh 0.0 - 0.1) during deposition and diagenesis (Krumbein and Garrels, 1952). These underlying deposits may be interpreted as representing epicontinental marine areas of normal salinity and open sea circulation.

Sediments of the evaporite unit are cyclic, and the dominant lithologies are limestone, argillaceous limestone, dolomitic limestone, gypsum, and anhydrite. The association of these sediments is suggestive of deposition in a restricted-sea environment. The carbonate components of the evaporite unit are unfossiliferous and may have been formed by primary precipitation, a physicochemical action that takes place without the assistance of living organisms. Certain intervals in the evaporite unit are composed of sugary dolomitic limestone that has a "sandy" texture, perhaps as a result of the reworking of the crystalline materials (Probably carbonate rhombs). in many zones of the evaporite unit the carbonate appears as oöliths, which either are isolated grains or are cemented together and thus resemble a cluster of grapes. The carbonate grains (Pseudo -oöliths) may have become rounded as a result of the agitation of sediments on the sea floor by wave-generated currents in carbonate -saturated waters.

A return from a restricted-sea environment to open-sea circulation is indicated by the sediments immediately overlying the evaporite unit. These sediments are predominately carbonate and locally contain many oöliths and much chert. As organic carbon or hydrocarbons also are lacking in these sediments, one may infer that the sediments overlying the evaporite unit and those underlying it were deposited in a similar environment.

Deposition of evaporites seems to follow the cyclic pattern set forth by Sloss (1953, p. 153), who believes that the major evaporite cycle is normal marine, penesaline, and normal marine. The up-

ward succession from the fossiliferous fragmental limestone (normal marine) to the limestone, argillaceous limestone, dolomitic limestone, gypsum, and anhydrite of the evaporite unit (penesaline) represents the "advancing restricted hernicycle." Subsequent deposition of limestones that are normally fossiliferous and cherty (normal marine) marks the "relaxing restricted hernicycle." One should note, however, that the complete cycle as set forth by Sloss is not represented in the evaporite unit. The saline environment characterized by halite and bittern sediments did not exist in the evaporite unit. Thus, one may infer that the concentration of marine salts was insufficient to permit chloride and "bittern" precipitation. The absence of fossils in the evaporite unit, however, implies that concentration of marine salts was sufficient to be toxic to normal marine life.

A gradation from the normal marine phase of sedimentation to that of the penesaline phase is suggested by the isopach rate of change, which reflects a segregation into various tectonic components (shelfs, basins, and hinge lines). Apparently in the advancing restricted hemicycle there is a tendency toward a higher degree of tectonic instability that results in the subdivision of the major basin into several intrasilled basins, whereas in the relaxing restricted herni-cycle there is a return to tectonic stability.

The termination of evaporite deposition possibly could have been brought about by (1) an increase in precipitation, which resulted in a supply of water being added to the basin of deposition, or (2) epeirogenic movement in basins and source areas prior to the deposition of sediments in the upper part of the St. Louis limestone. The latter explanation for the termination of evaporite deposition is substantiated by the dominant limestone deposition in the upper part of the St. Louis. This deposition of limestone may indicate that a change from restricted-sea environment to open-sea circulation took place. Because the areas to the northeast were higher than those to the southwest, the southern area probably sank below sea level, and then the sea began to encroach northeastward. The addition of sea water from the south terminated evaporite deposition and permitted the deposition of limestone.

CONCLUSIONS

Subsurface studies in southwestern Indiana show that evaporites (gypsum and anhydrite) are found in the lower part of the St. Louis limestone.

Three major intrasilled basins exist in southwestern Indiana: one in southwestern Orange County, northern Spencer County, Perry County, and southwestern Crawford County; one in central and west

ern Martin County and eastern Daviess County; and one in northern Greene County, southwestern Owen County, and southern Clay County. Maximum accumulation of evaporites is found in these intrasilled basins.

The evaporite cycle of marine, penesaline, and marine results from both tectonic and environmental causes.

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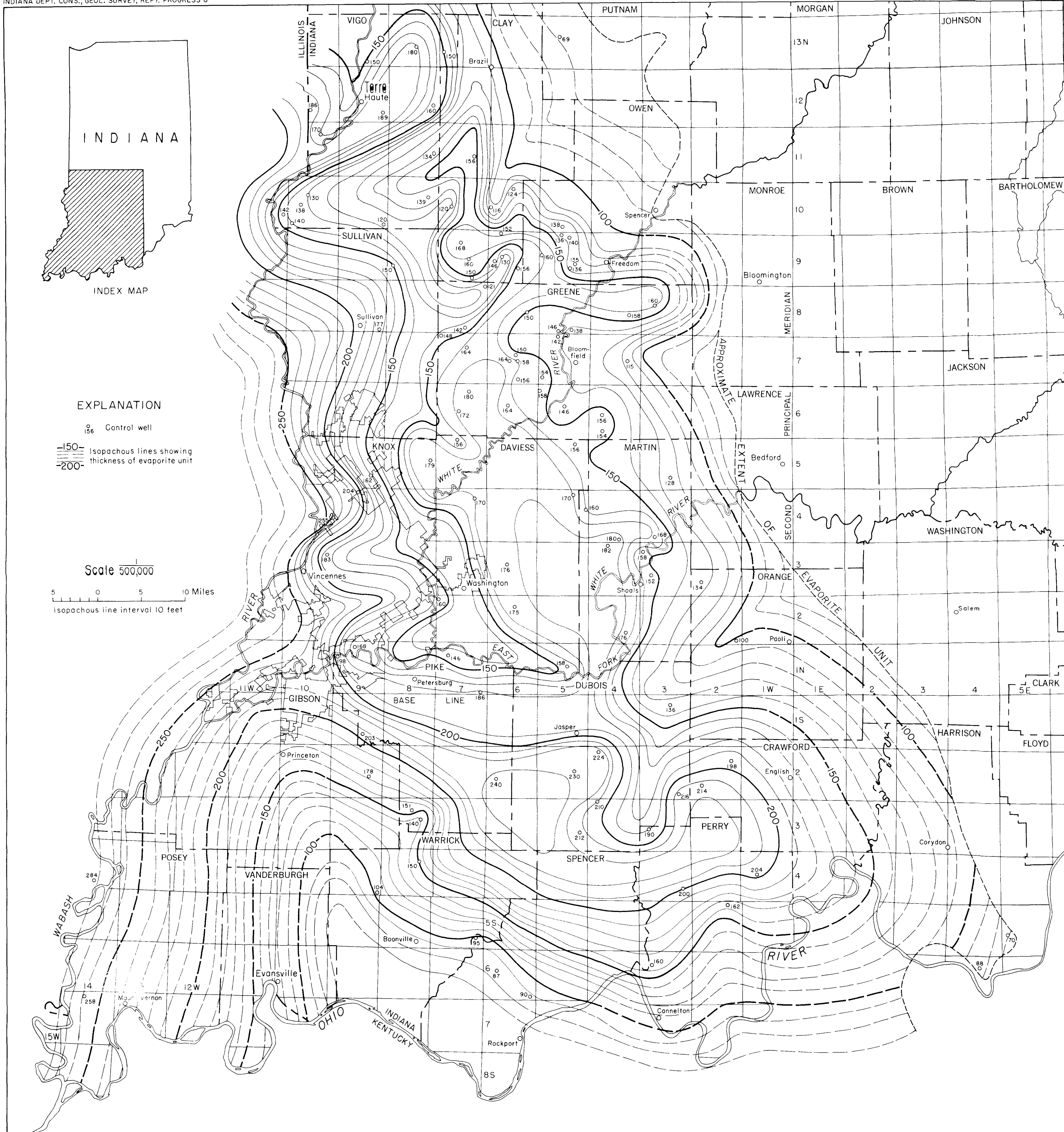
INDIANA

INDEX MAP

EXPLANATION

o
156   Control well

—150— Isopachous lines showing
—200— thickness of evaporite unit

Scale 1/500,000

5   0   5   10 Miles

Isopachous line interval 10 feet

MAP OF SOUTHWESTERN INDIANA SHOWING ISOPACH OF LOWER ST. LOUIS LIMESTONE (EVAPORITE UNIT)
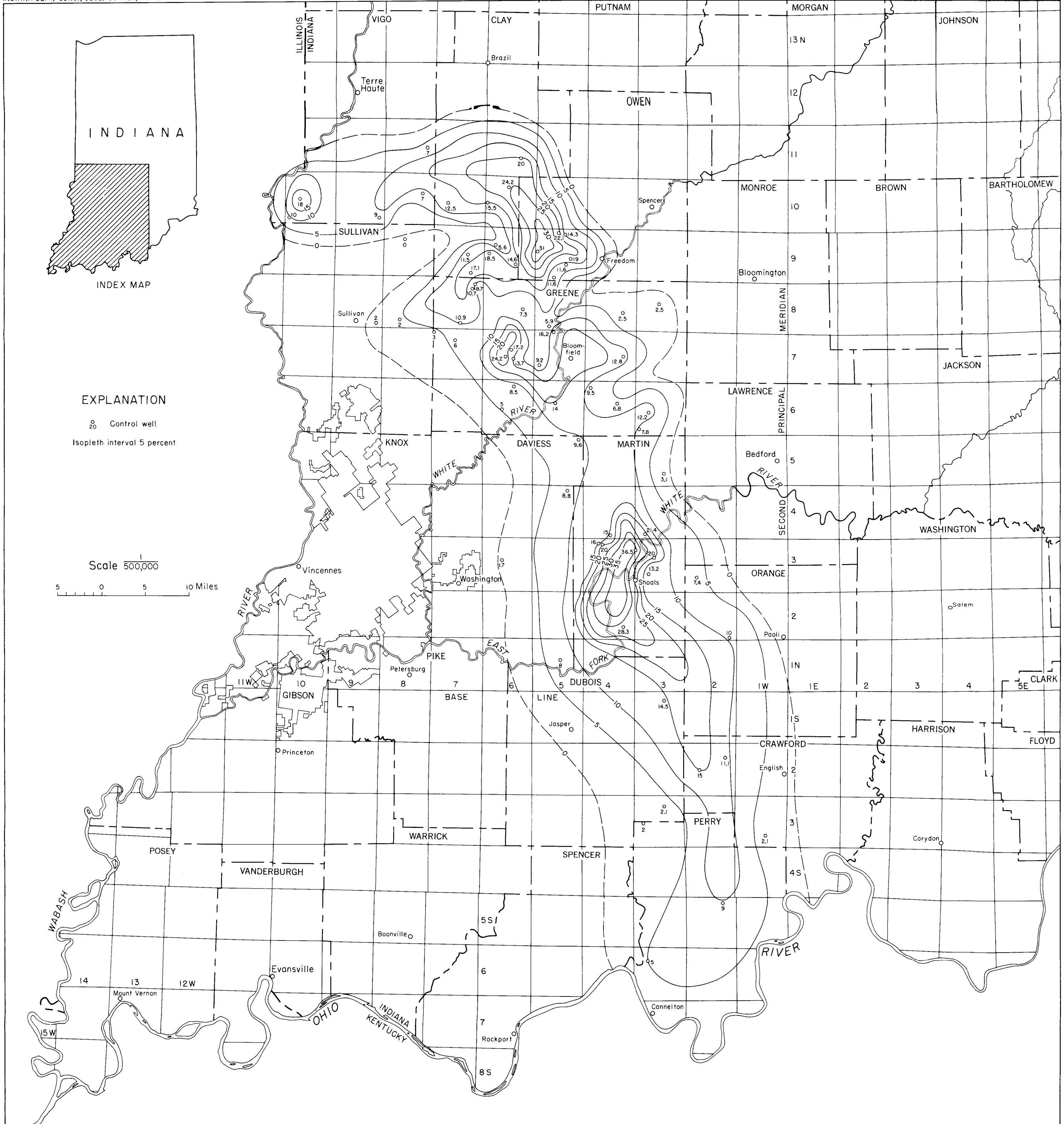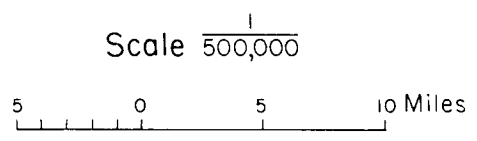
MAP OF SOUTHWESTERN INDIANA SHOWING PERCENT OF EVAPORITES
IN LOWER ST. LOUIS LIMESTONE (EVAPORITE UNIT)