SEDIMENTOLOGY OF THE SALEM LIMESTONE IN INDIANA

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ABSTRACT

The Mississippian Salem Limestone, from which dimension stone is quarried in Indiana, is principally a calcarenitic rock formed of fossil bryozoans, echinoderms, and specimens of *Endothyra*.

Numerical associations of the fossils, binding materials, oölitically coated fossils, and voids were determined by counting points on the surfaces of 278 thin sections of the limestone. Median sizes, coefficients of sorting, and skewness numbers were computed from measurements made of constituents in these thin sections. Many other samples and numerous exposures of the Salem and contiguous parts of adjacent formations also were studied.

The organisms that furnished the skeletal material for formation of the Salem Limestone were chiefly gregarious and communal. Salem rocks are formed of nearly whole skeletons, of dismembered or slightly damaged skeletons, and of skeletons thoroughly ground up, because currents in the Salem sea varied in their ability to move and damage these materials. Locally the sediments are of uniform grain size because of sorting by currents and because related organisms grew to similar sizes. Rocks of the formation

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contain different proportions of the fauna both because the animals lived in these proportions and because their skeletons were mixed together by currents.

The proportional relationships between members of the fauna were constant locally and for short periods of time. Study and mapping of the faunal associations, numbers of oölitically coated fossils, bedding structures, and size parameters enables geologists to suggest sedimentologic histories and sequences in areas of various sizes. Interpretations based upon such areal studies are necessary for evaluation of the dimension-stone potential within the Salem Limestone.

INTRODUCTION

The Salem Limestone, from which Indiana's dimension limestone is quarried, is Meramecian (Mississippian) in age. It overlies the Harrodsburg Limestone and is overlain by the St. Louis Limestone; the relationships are conformable with possible local exceptions between the Salem and St. Louis.

The work summarized here is the result of field studies of 41 measured sections in Indiana, and laboratory studies of about 750 polished sections and 880 thin sections made from samples obtained from the field. Parts of the author's work on the Salem have been reported previously (Smith, 1955, 1957, and 1962) and, at the present time, the Indiana Geological Survey is considering for publication a manuscript by the author titled "Petrography and economic geology of the Salem Limestone." The specific details described in the present report are the result of detailed point counting of materials found on the surfaces of 278 thin sections from those 12 of the 41 measured sections mentioned above that are shown on Table 1.

TABLE 1

Locations and types of measured sections

Section Number*	Location	Type of section
	Harrison County	
1	SE¼ sec. 1, T. 6 S., R. 4 E.	Quarry and road cut
	Washington County	
2	NE¼NE¼ sec. 28, T. 1 N., R. 4 E.	Quarry and road ditch
3	NW¼SE¼ sec. 24, T. 2 N., R. 4 E.	Railroad cut
4	NE¼ sec. 24, T. 2 N., R. 3 E.	Quarry
	Lawrence County	
5	NW¼NE¼ sec. 34, T. 5 N., R. 1 W.	Road cut
6	NW¼NW¼ sec. 26, T. 5 N., R. 1 W.	Road cut
7	NE¼NE¼ sec. 25, T. 5 N., R. 1 W.	Quarry
8	SE¼SW¼ sec. 16, T. 6 N., R. 1 W.	Quarry and cores
	Monroe County	
9	NW¼SW¼ sec. 36, T. 8 N., R. 2 W.	Quarry
10	SE¼SE¼ sec. 32, T. 8 N., R. 1 W.	Quarry
11	SE¼NW¼ sec. 20, T. 10 N., R. 2 W.	Quarry
	Putnam County	
12	NW¼NW¼ sec. 29, T. 14 N., R. 4 W.	Cores

*Number corresponds to numbers shown on figure 2.

The present report attempts both to show a quantitative basis for a sedimentologic history of the Salem Limestone and to show a means of subdividing the limestone into units of economic importance, that will simplify exploration for dimension limestone.

Part of the work was done while the author was an employee of the Indiana Geological Survey, and part as a student in Indiana University. The author appreciates the permission of the State Geologist, Dr. John B. Patton, for the use of the Survey equipment needed during this study.

DESCRIPTION OF THE SALEM LIMESTONE

Thickness and Distribution

The Salem Limestone is exposed, in Indiana, from the Ohio River about 27 miles downstream from Louisville, Kentucky, northward to near the common intersection of Fountain, Montgomery, and Parke Counties, about 57 miles west-northwest of Indianapolis. The principal outcrop belt follows the Ohio River along the eastern boundary of Harrison County through western Floyd County and northward to the vicinity of Salem, in Washington County. From Salem, the outcrop belt extends northwestward to Bedford, Lawrence County, and then northward to Bloomington, Monroe County, where it veers to the northwest again. North of the White River in Owen and Putnam Counties, the limestone is largely covered by glacial debris, but it is exposed locally in a belt that can be traced north from the river to just east of Greencastle, Putnam County, and thence northwestward to the same common intersection of Fountain, Montgomery, and Parke Counties described above. The dimension-limestone industry based on the Salem Limestone is located in Lawrence and Monroe Counties, between the White River and the East Fork of the White River.

The Salem Limestone reaches a total thickness of nearly 100 feet in the central part of the dimension-limestone belt, but it thins to only a few feet at the extreme northern end of its outcrop. Where the dimension stone is quarried, its thickness is generally from 40 to 60 feet. Southward from the dimension-stone area, the limestone is from 55 to 75 feet thick. It is known to be absent because of non-deposition north of Putnam County.

Bedding ranges from thin and fissile to units up to 40 feet thick, which are unmarked by partings or bedding planes, but usually contain stylolites.

Constituents

The Salem Limestone is a carbonate-rock unit in which most of the constituents are sand-sized, fossilized debris of marine organisms. Minor parts of the limestone, which have economic significance as waste stone, are formed of carbonate materials of mixed grain sizes. In Grabau's classification (1960, p. 287 and 294), the Salem Limestone is chiefly a calcarenite, with minor amounts of calcilutite and calcirudite. In Folk's classification (1959, p. 18 and 24), it would be called a biomicrite and biosparite in which the clasts are fossilized debris from marine organisms.

Bits and pieces of lacy, fenestrate bryozoans are the chief constituents of the Salem Limestone. Evidence for this identification (fig. 1) consists of zooecia, in which zooecial apertures could be observed, and of cylindrical, knobby, and rod-like segments of zoaria broken from the rest of the colony by fracturing of the non-cellular dissepiments. Most of the bryozoan fragments observed in thin sections of rock are 0.2 to 1.0 mm in long diameter.

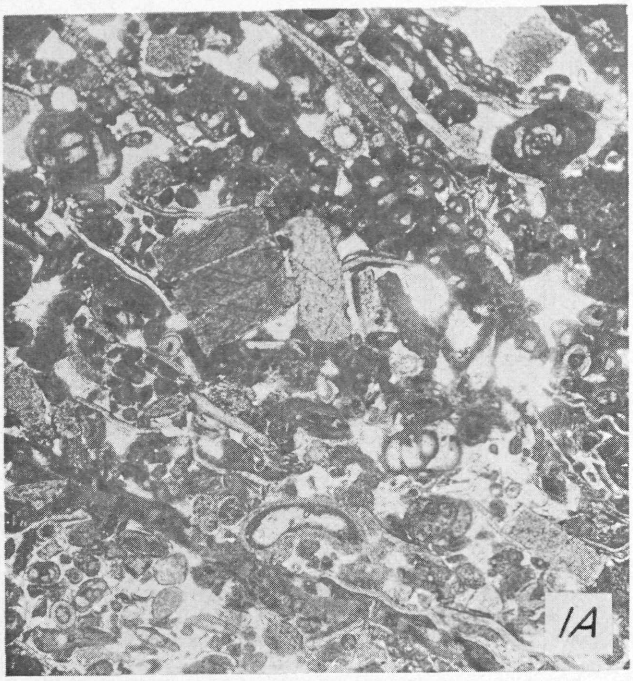
Next in abundance are plates from echinoderms (fig. 1), chiefly from crinoids and blastoids. Echinoderm plates are optically single crystals of calcite, and display structures radiating from the axial canal of columnals, longitudinal ribs along spine-like tubes, or a cross-hatched or reticulate appearance. Echinoderm plates are usually between 0.5 and 1.0 mm average length in most samples, but have been found in sizes ranging from 0.1 to 2.2 mm.

Specimens of *Endothyra baileyi* Hall (fig. 1A) are easy to find and identify in the Salem Limestone. This foraminifer has several whorls of bulbous chambers, with each whorl changing direction every 30 to 90 degrees. Sections cut through

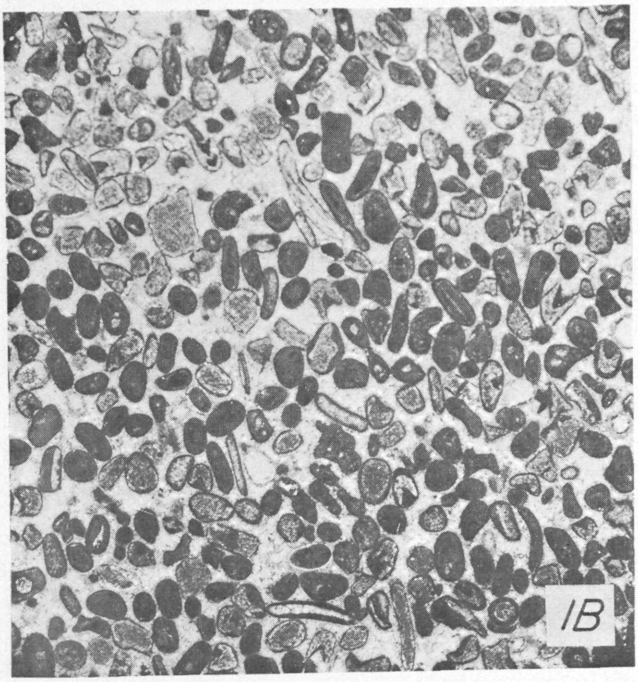
EXPLANATION OF FIGURE 1

FIGURE 1. Constituents commonly found in the Salem Limestone (plane polarized light; magnification 20×).

A. Coarse size, fragmented fossils not oölitically coated
B. Medium size, fragmented fossils oölitically coated



1A



1B

the ultimate whorl and the proloculum are best for classification, but other sections are usable, once the general appearance of the skeleton is known. Specimens of *Endothyra* ranging from 0.3 to 1.4 mm have been observed, but most adults are about 0.8 or 0.9 mm in largest diameter.

Marine organisms, other than those described above, are not quantitatively important in the Salem Limestone. Among the miscellaneous fossils present are ostracods, high- and low-spired gastropods, pelecypods, brachipods, sponge spicules, algae, and fishes. Also included in the miscellaneous category are pieces of calcite that have sharp, mainly irregular boundaries, ghosts of organic structures, or some streakiness or ordered arrangement not found in agglutinations of calcite. The miscellaneous category includes the largest and smallest pieces encountered in thin sections; these range from 0.1 to about 4 mm, though larger specimens were observed in outcrops.

The fossil debris in the Salem Limestone is bound together (fig. 1) by calcite cement and calcite matrix. The differentiation between cement and matrix is made on the largely arbitrary bases of size and optical properties though there is a continuous sequence of these characteristics. Some of the material called matrix has sharp, irregular boundaries, like those of fossils, or displays internal structures suggestive of fossils. The author believes that some or all of this material is the product of mechanical grinding of skeletal material into carbonate mud or mechanical ooze, and is therefore properly called matrix instead of cement.

Optically clear calcite occurs throughout the Salem Limestone in masses larger than 0.05 mm; this material is called spar. It is also called cement (1) if it appears to be interstitial; (2) if it lacks borders, ghosts, or other suggestions of fossil origin; and, especially, (3) if it occurs as outgrowths from fossils or interstitial calcite. Cement in the Salem Limestone is clearly the result of precipitation of calcium carbonate, as well as recrystallization of matrix and framework material.

Other minerals present, usually in insignificant amounts, are dolomite, quartz, pyrite, hydrous iron oxides of several varieties, clay minerals, and a few other minerals.

Also included as constituents of the Salem Limestone are the void spaces, because voids are textural elements that influence the commercial value of dimension limestone produced from the formation. Differentiation of the different kinds of voids in the rock is not always possible. Original interstitial spaces (pores), vugs formed by differential solution or other processes, and places where grains have been plucked out during the preparation of thin sections and polished sections are all observed in the limestone. Pores tend to be the same size as the framework grains; local variations in the size and distribution of voids simulate irregularities in grain size and give the rock a granular appearance.

The Salem Limestone is not an oölitic limestone, since it is not composed of oölites. The nearest approximation to an oölitic texture is illustrated in figure 1B, in which several grains are coated by concentrically disposed calcite that represents the beginnings of oölite formation. These coatings are relatively thin compared with the diameters of the fossil debris.

Some of the microcrystals of calcite in the Salem Limestone occur in silt- or sand-sized aggregations or agglutinations called pellets, but these are quantitaitvely rare in the samples studied. Pellets lack internal organization and regular habit, but have distinct smooth boundaries with neighboring materials or with voids. Fossils and calcispheres have been observed within pellets in non-central or non-nuclear positions, but pellets are not considered to be oölites.

SEDIMENTOLOGY

Generalizations

Current-produced structures in much of the Salem Limestone show that the places where the fossils are found now are probably not the life habitats. Indeed, evidence suggests that the habitats of fossils were far removed from some present places of accumulation. This study was not concerned with the habitat of the living organisms, however, but with the place and mode of deposition of all the materials, and the resulting textural characteristics, information from which stratigraphic and economic interpretations could be made.

Nearly whole fronds of fenestrate bryozoans (fig. 1) found in the Salem Limestone accumulated either in piles of haphazardly arranged, contorted, and crushed individuals, or in horizontal laminations. The first type of accumulation shows that the fronds were moved short distances and then were deposited and buried rapidly. The second suggests either a lack of transportation or slow sedimentation in a low-energy environment—much as leaves drift down in the absence of wind. More minutely broken debris of bryozoans are found in cross-bedded, current-lineated, and shingled accumulations that show size reduction by, transportation in, and deposition from moving currents of water.

The echinoderms and *Endothyra* (fig. 1) held up well under the energy conditions of the Salem environment. Some echinoderm plates show rounding and breaking to a minor degree, but *Endothyra* seldom was damaged at all. This may be due to the fact that *Endothyra* was a chambered organism whose buoyancy might have protected the skeleton from damage. Minority members of the fauna give little evidence of damage beyond disarticulation of valves and removal of spines. However, these pieces are very useful in sedimentological studies because of their usually large and flattish shapes, which show imbrication, orientation, or lamination by currents.

In connection with studies of abundance and evidence of damage to fossils, designed to produce knowledge of energies and other conditions of the environment, the problem of identification of organic remains must be kept in mind. Bryozoans have very small internal structures, which enable the observer to identify their remains in small debris. A few breaks in a single-crystal plate from an echinoderm, however, leave the pieces indistinguishable from other pieces of crystals of calcite. Thus, the relatively large amounts of miscellaneous fossil debris do not mean that the minority members of the fauna were great in abundance, but that, in all likelihood, the echinoderms were probably in greater abundance than the results show, and that *Endothyra* was probably not as significant in the habitat of the living organisms as it is in the rocks in which we find their remains.

Various constituents of the Salem Limestone are so ubiquitous that associations between them are more revealing than sheer numbers. Comparative studies of the abundances of the organisms, ratios relating one form to another, and size data laboriously obtained with an ocular micrometer show that the energies involved in the Salem sea varied and that the chief organisms, which were gregarious forms attached to the floor of the sea, lived both communally and in separate communes of like animals. Some beds lack current structures and consist of accumulations of all kinds of fossils of widely differing sizes. In such accumulations, the similar parts of similar organisms have a range of sizes that show that the animals grew to different sizes. Other accumulations consist of the remains of a single type of organism, again with a wide range of sizes of the individual pieces, which show that the organisms grew to different stages of maturity.

Most of the Salem Limestone, however, has current structures and constituents of very uniform size, which suggests that the environment of deposition was such that uniform sizes were sorted out and deposited together. For example, the quantity of *Endothyra* increases with increasing quantities of echinoderm plates whose sizes are near that of *Endothyra*, and decreases as the size of bryozoan fragments decreases. *Endothyra* and plates from echinoderms accumulated together because they were similar in grain size; mechanically stable bits of bryozoans are much smaller than the general size of *Endothyra* and therefore were not accumulated in the same deposits. Accumulations of large, relatively undamaged fenestrate bryozoans do not contain many specimens of *Endothyra* because of size sorting, or because the two types of organisms did not live and mix profusely in the same habitat.

The ratio of fossils to binding material in most places is greater than 1; such a ratio is a characteristic of the dimension stone of the formation. As the amount of binder increases, the variety of fossil debris decreases, until usually only bryozoan remains are identifiable in rock which consists mainly of matrix (or groundmass). Such rocks characteristically will contain a few specimens of *Endothyra*, probably because *Endothyra* was either a swimming or floating form and dropped to the bottom after death. The data suggest very strongly that the matrix is debris from broken bryozoans. This conclusion must be tempered with the thought that the echinoderm fragments are almost impossible to identify when they have been reduced to this size, a size in which bryozoan materials may still be easily identified.

The number of fossil grains that are oölitically coated tends to increase with an increase in the amount of matrix material; there is no preferential coating of a particular type of organic remains. This evidence, coupled with the fact that none of the Salem Limestone is composed entirely of oölitically coated fossils, shows that the oölitic coatings were added mechanically and were not precipitated chemically. Further evidence of mechanical application of oölitic coatings may be found from a study of the echinoderm fragments; the coatings are not in optical continuity with the single-crystal echinoderm plates, except where evidence of recrystallization is present. Changes in the ratio of binder to coated fossils has a significance that can be observed in the field. Units containing many oölitically coated fossil remains can be traced laterally into rock containing an increased amount of binder around oölitically coated fragments, and on into rock that is all matrix (calcilutite); such rock is waste as far as the dimension-stone industry is concerned.

Median sizes (figures 2 and 3), sorting coefficients, and skewness numbers were determined for the thin sections studied in detail; an ocular micrometer was used to collect size data. Most of the samples had median sizes of 0.5 to 0.7 mm; fewer than 10 percent had median sizes in the silt range. Large median sizes were found for samples having a large content of echinoderms, and small median sizes were found for those having both a large content of bryozoans and a small content of miscellaneous fossils. The clear trend toward fewer identifiable fossils as the median size decreases is the result of the loss of identifying characteristics as fossils were broken up.

The data show the Salem Limestone to be well sorted. Sorting is good because the particles were mechanically sorted for most of the formation and because they are from organisms that grew parts to similar sizes. Decreasing median sizes are accompanied by increasing sorting coefficients, which probably means that chemical precipitation occurred locally, as well as mechanical sorting and deposition of small sizes.

If the same rules are applied to the Salem Limestone as are commonly applied to a unit of quartzose rock in the shale-silt-sand size range, then the Salem should be called a "mature" sediment, but it undoubtedly matured faster, and with the expenditure of less energy than a unit made of mechanically more durable quartz.

Chiefly there is a high correlation between large numbers of coated grains and low sorting coefficients. There is, however, a curious relationship in which oölitically coated grains of medium or smaller grain size occur with either larger or smaller sizes of uncoated grains in poorly sorted mixtures, or with uncoated grains in very well-sorted mixtures. The data suggest that the oölitically coated grains have been removed from the place where the coatings were formed and redeposited in a new locale. At least some second-cycle carbonate sediments, and perhaps carbonate sediments of more than two cycles, may be present in the Salem Limestone.

Summary History

Early Salem rocks are very similar to the rocks in the underlying Harrodsburg Limestone. The fossil materials were not subjected to much fragmenting activity and were not close to a land mass contributing much material other than calcium to the sea. In progressively younger Salem rocks, the evidence of current activity increases, and the degree of fragmentation of the skeletal remains increases. Faunally the Salem resembles the Harrodsburg Limestone, except for the addition of the foraminifer *Endothyra*, which is exceedingly rare in the Harrodsburg. The major difference between the two formations is the presence of oölitically coated fossils. The environment needed for producing oölitic coatings developed during the first third of Salem time. This is interpreted to indicate a further increase in the energy of the Salem environment over that the Harrodsburg environment.

Locally, at different times, the Salem sea became a higher energy environment and moved, shifted, and redeposited the available materials; the amount of energy and the direction of currents varied greatly. Salem lithologies tend to change more rapidly horizontally than vertically. Small pockets of pebble-size fossils lagged behind as the finer sizes were winnowed out and deposited elsewhere. In some localities, water loaded with silt and mud sizes apparently lost most of its capacity, and deposited lime muds. Later, particles from organisms were rolled through this mud and became coated. At times, skeletons of gregarious organisms were allowed to accumulate, relatively undisturbed by currents, in the areas where they lived.

The Salem Limestone, therefore, must have accumulated in marine waters either distant from land or close to a land that contributed chiefly calcium to the sea. In either case, the chief land contributions came from the north, and the deepest parts of the sea were in the southern part of Indiana. Younger Salem rocks were formed either in deeper water or in a restricted basin.

Since final deposition of the Salem, there has been little addition or subtraction of material, either from sea water, ground water, or connate water. The color of the Salem must result chiefly from finely disseminated soft parts of organic material and small bits of iron-bearing minerals in the rock. Since uplift above sea level, local differential solution and redeposition have caused some recrystallization of the original fossil debris and have altered the color of the rock through oxidation of the organic soft parts and the iron-bearing minerals.

APPLICATIONS OF THE STUDY

The most obvious application of this study lies in the internal stratigraphy of the Salem Limestone. Throughout Indiana, though typical Salem Limestone was easily identified, some variations within the formation were more difficult to recognize. This problem has been acute in the dimension-stone industry, where failure to recognize some lithologic types as belonging to the Salem Limestone has resulted in such erroneous assumptions as the absence of this unit in economically and stratigraphically strategic areas. Parts of the limestone are lithologically very similar in appearance to the underlying and overlying formations; failure to recognize these lithologies as belonging to the Salem Limestone has led, in some cases, to the abandonment of quarry sites, because an adjacent formation was mistakenly thought to have been encountered when in fact economic thicknesses of Salem dimension stone were still available above or below. There is no doubt that knowledge of the internal stratigraphy, which was developed by local depositional conditions and was dependent upon the type of skeletal materials available, is necessary in order to utilize the formation properly as a future source of dimension stone.

Initial subdivision of the Salem can be accomplished by using the ratio of fossils to binding material. This primary subdivision can be further subdivided on the basis of bedding, oölitic coatings, and of fauna. A continuous progression

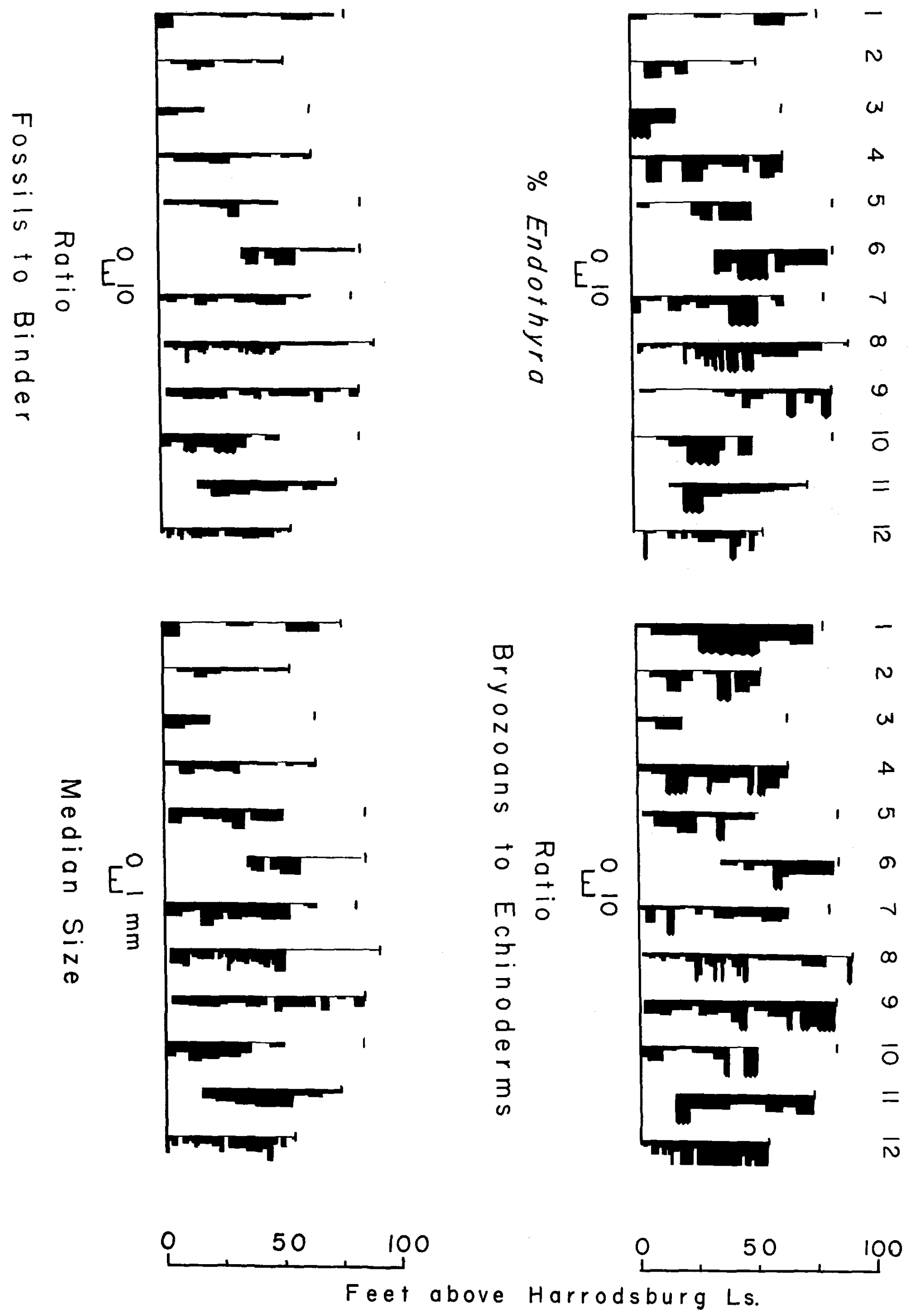


FIGURE 2. Stratigraphic and geographic distribution of common constituents and sizes found in the Salem Limestone in Indiana. Numbers refer to locations given in table 1. Bars at top of each column show approximate base of the St. Louis Limestone.

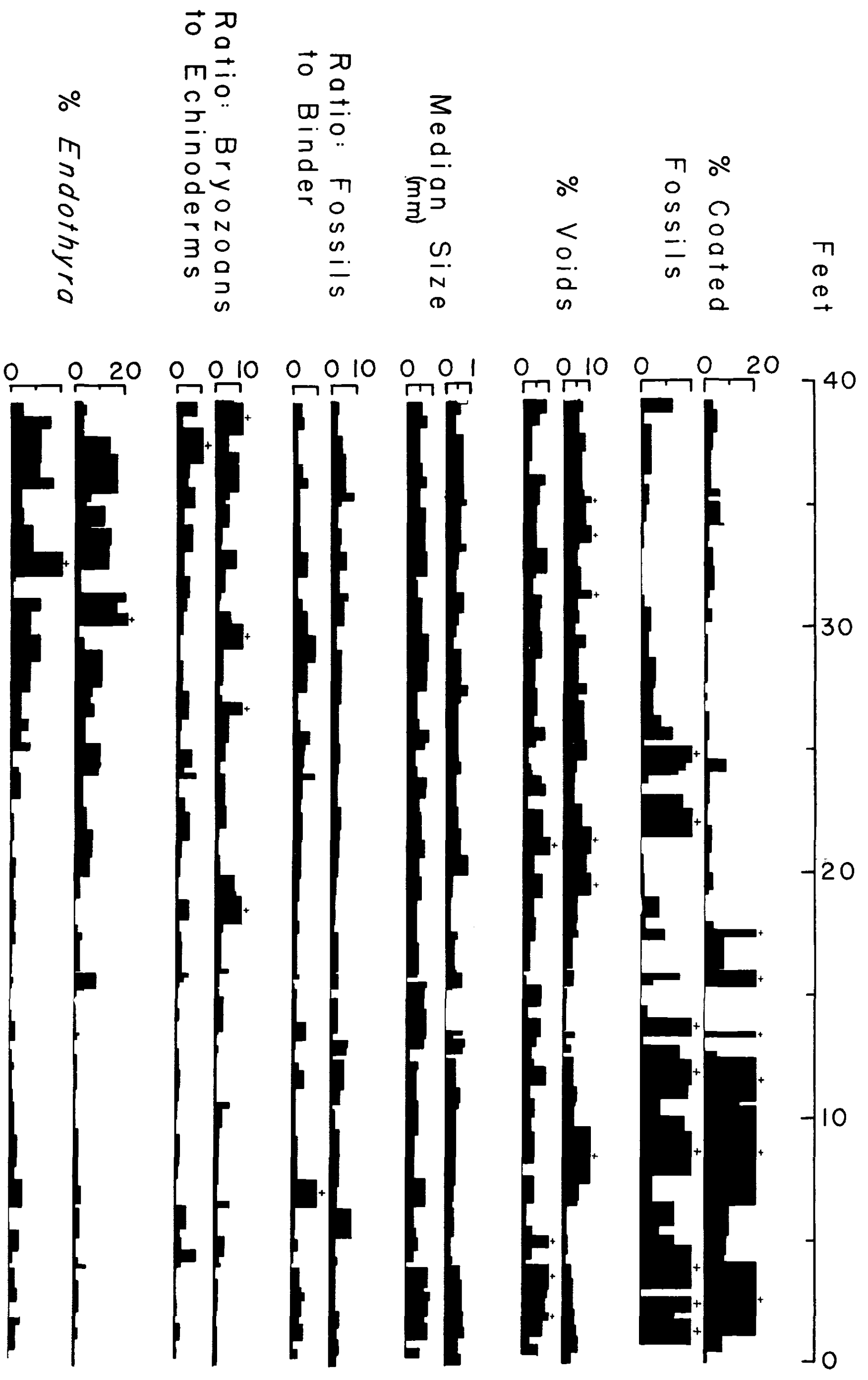


FIGURE 3. Distribution of common constituents and sizes found in two cores of the Salem Limestone obtained at locality 8. (See table 1 for location.)

of carbonate sediments has been found in the Salem from rock formed entirely of microscrystals through arenites to rudites formed entirely of fossils bound together by very little material.

On a state-wide basis, there are only a few similarities in the distribution of constituents and size parameters between measured sections as widely spaced as those shown on figure 2. For example, there are two or three stratigraphic positions at which *Endothyra* is in good abundance; the association of *Endothyra* with other constituents differs in each of these three zones, making them useful stratigraphic markers. Another example is the upward decrease in percentage of grains that are oölitically coated. Most of the rocks containing more matrix than fossils are found in the upper third of the formation. In the lower two-thirds, such high-matrix rocks do not persist over large areas, but are good markers in the small areas where they are present.

On a smaller scale, illustrated by the data shown on figure 3, taken from two cores 283 feet apart, some useful similarities and differences may be seen. The kinds of data collected show features of the sedimentologic history of the formation in a small area, such as, for example, the direction of current movement. This kind of information, coupled with the knowledge that certain stone is economically valuable and other stone is not, can be applied to find the direction of thickening, or of decreasing grain size, or of any other change in character that might affect the economic value of the stone. Other cores could be taken to check this picture or to give additional information.

Approximately the same results can be obtained without detailed point counting in thin sections, but merely by estimation of the same relationships with a hand lens. Accuracy and fineness of detail are lost, however, and the results suffer accordingly. However, one must weigh the cost of thin sections and the time spent using the polarizing microscope against the cutting of more cores. To one extremely familiar with the Salem Limestone, the process of cutting more cores and working by estimation would prove to be cheaper and almost as accurate.

The environment of deposition and the materials available were not so uniform that perfect predictability could be achieved. Some of the sedimentation units that ruin the commercial value of the stone are small enough to be missed completely by cores on any reasonable spacing. Also, stray bits and pieces of large fossils may be found within otherwise well-sorted material; small irregularities of texture occur for no predictable reasons. But careful sedimentologic studies of carefully located cores can increase the chances of success.

As a result of these studies, the requirements for the different commercial grades may be described in geologic terms. Statuary and select grades are obtained from very fine- to medium-grained, well sorted calcarenites lacking large-sized fossils and vugs. These calcarenites represent sediments which were deposited rapidly, possibly were derived from previously sorted materials, or were uniformly bound together so that laminations have been obscured. These desirable grades are made up mostly of bryozoans and are closely related to the undesirable laminated or non-laminated calcilutites (formed entirely of ground-up fossils or matrix).

Standard-grade stone is not necessarily unsorted, but rather has an irregular occurrence of grain sizes, pores, or binding material; most standard stone has laminations, either horizontal, inclined, or cross-bedded. Most standard stone is characterized by an abundance of *Endothyra* and by a median grain size near 1.0 mm. The "rustic" grade is either poorly sorted or has been intensively subjected to differential solution, recrystallization, and recementation.

The ideal dimension stone sought by quarriers is a massive even-textured, medium-grained, bryozoan-rich rock containing few echinoderm plates and specimens of *Endothyra*. This stone, which is formed of zooaria of fenestrate bryozoans, broken along dissepiments down to the length of a few zooecia, should compose an evenly cemented jumbled mass, unbroken by stylolites or other partings. Quarriers will settle for a medium-grained calcarenite in which most fossils are oölitically coated, if the oölitic coatings are obscured by an evenly distributed binding material of about the same milky white color as the coatings. The channeling machines end up cutting more mixed-fauna calcarenite of coarse grain than the more desirable bryozoan calcarenite of finer grain sizes.

Unacceptable are unsorted and dense stone of any variety, unevenly cemented stone, stone with most grains in the silt to very fine-grain sizes, and stone containing irregularly distributed coarse voids. The occurrence of more than one stylolite in less than four feet of rock is an economic disaster that may be reflected by a rise in unemployment in two counties.

Some of the stone that is quarried in Indiana is actually part of the subjacent Harrdosburg Limestone. As long as a geologist does not identify this formation for a quarrier, the quarrier is cheerful all the way to the bank. But should he get the idea that certain stone is really part of the Harrodsburg Limestone, he will refuse to quarry it no matter how attractive the texture and color. Similarly, if a quarrier should find stone in a hillside that appears to belong to the St. Louis Limestone, no amount of talk will convince him that salable stone could possibly be found higher in the hill. Such foibles need to be considered seriously by any geologist attempting to locate a dimension-stone quarry site. Little can be done about the foibles, but much can be done to aid in finding premium grades of dimension stone, provided the geologist has patience and financial support.

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