PETROLOGY OF MARINE BANK LIMESTONES OF LANSING GROUP (Pennsylvanian), SOUTHEAST KANSAS

by

John W. Harbaugh

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ILLUSTRATIONS

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ABSTRACT

Limestones of the Lansing Group in the Wilson-Montgomery County, Kansas, area contain small patches of coarsely crystalline calcite that exhibit two types of fabric, one formed by precipitation of calcium carbonate in cavities; the other by recrystallization of carbonate silt or fine skeletal debris by a process termed grain growth.

Filled cavities are associated with leaflike fragments of algal crusts; which, during deposition, served as umbrellas, catching carbonate silt and skeletal debris on their upper surfaces and maintaining sheltered open spaces beneath. Cavities also were formed between fragments of partly consolidated carbonate silt that formed sedimentary breccias.

Algal crusts and fragments of other organisms tended to accumulate in thickened lenses or banks, which rose above the level of the surrounding sea floor and extended over many square miles. The banks were seemingly too poorly consolidated initially to have formed wave-resistant reefs.

Solution pores in Lansing limestone specimens obtained at outcrops show that small-scale lithologic features have exerted a large effect in localizing pores. Many pores occur within coarsely crystalline mosaics, particularly those formed as open-space precipitates. Other pores are localized at the boundaries of mosaics, at the contacts between individual skeletal particles, within algal crusts, and within dolomitized patches. Fractures, both large and small, also have had large influence in localizing pores. Development of porosity in buried Lansing limestones that serve as oil-reservoir rocks may be influenced similarly.

INTRODUCTION

Increasing interest in the study of microscopic aspects of limestones has been stimulated by large-scale development of oil reserves in limestone reservoir rocks. It is now generally recognized that microscopic features affect oil reservoir characteristics of limestones by influencing development of solution porosity. It is the purpose of this report to describe and interpret fabric and other microscopic features of marine bank limestones of the Lansing Group (Pennsylvanian) in Wilson and Montgomery Counties and to show how these features have influenced development of porosity (Fig. 1).

This report is an outgrowth of an earlier study (Harbaugh, 1959) dealing with development of a marine bank in the Plattsburg Limestone of the Lansing Group. The present report is based on further study of the Plattsburg Limestone, and also includes study of the limestone members of the Stanton Limestone of the Lansing Group. Conclusions drawn in these studies, although based on examination of outcropping rocks in a small area, probably are at least partly applicable to buried limestones of similar age serving as oil-reservoir rocks in central and western Kansas.

The term marine bank is used in this paper as a general term to denote a deposit that is interpreted as having formed on a submerged shallow area rising above the general level of the surrounding sea floor. The term does not imply an appreciable degree of wave resistance, as does the term reef, nor does it necessarily imply organic origin, as does the term bioherm. The term fabric is used here as a general term embracing the shape, size, orientation, and spatial interrelations of crystal grains.

This report is based on study of about 300 limestone specimens by means of acetate peels. Acetate peels reveal the microscopic details of limestones even better than do thin sections. The technique of making the peels employed in this study has been outlined previously (Harbaugh, 1959, p. 295).

The Lansing Group consists of alternating limestone and shale, divided into formations and members (Table 1). The Lansing Group is a division of the Missourian Stage, which in turn is a division of the Upper Pennsylvanian Series. The Spring Hill Limestone member of the Plattsburg Limestone has received the most microscopic study, followed by the Captain
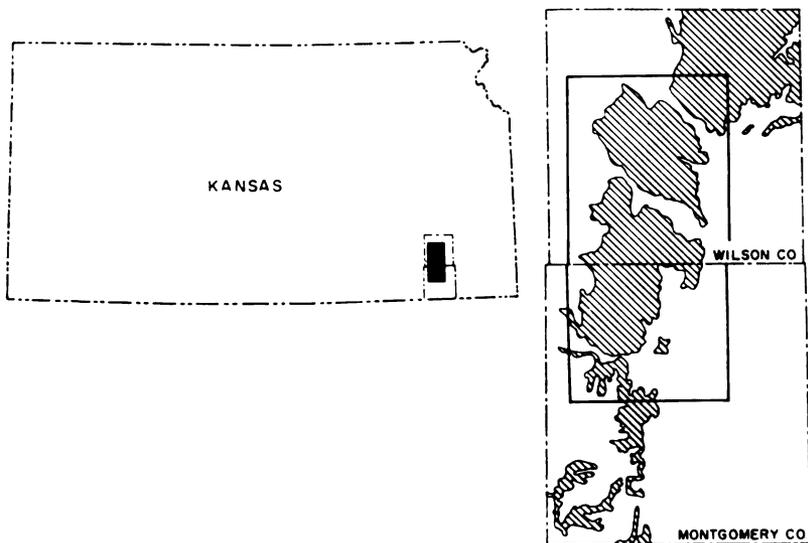
Fig. 1. Index map showing location of area of study in Wilson and Montgomery Counties. Outcrop belt of Lansing Group is diagonally ruled.

Creek and Stoner Limestone members of the Stanton Limestone. The Merriam Limestone member of the Plattsburg Limestone and the South Bend Limestone member of the Stanton Limestone have received relatively little microscopic study.

TABLE 1.—*Divisions of Lansing Group*

Stanton Limestone
        South Bend Limestone member
        Rock Lake Shale member
        Stoner Limestone member
        Eudora Shale member
        Captain Creek Limestone member
Vilas Shale
Plattsburg Limestone
        Spring Hill Limestone member
        Hickory Creek Shale member
        Merriam Limestone member

son of the Illinois Geological Survey, R. G. C. Bathurst of the University of Liverpool, and Holly Wagner of the U. S. Geological Survey, who helped in clarifying some of the ideas presented here. Others to whom I am indebted include Virgil Burgat of the State Highway Commission of Kansas for copies of unpublished engineering geological reports, Kenji Konishi of the U. S. Geological Survey for examining specimens of calcareous algae, and John Davis of the University of Kansas for intermittent accompaniment in the field.

LIMESTONE TYPES

Before entering upon a detailed consideration of the microscopic aspects of Lansing limestones, it will be useful to consider the six generalized types of limestone in the Lansing Group in Wilson and Montgomery Counties. These limestone types are defined more or less arbitrarily, because they intergrade and cannot be sharply distinguished from each other.

ALGAL-CRUST LIMESTONE

Limestone classed in this study as algal-crust limestone is characterized by an abundance of encrusted, leaflike fragments derived from several types of calcareous algae. The fragments are commonly crinkly, resembling lettuce leaves. Some of the fragments are of an alga surficially resembling *Anchicodium* and others have been derived from algae generally classed as *Spongiostromata*. Positive identifications, however, have not been made, because of lack of internal details within the algal crusts. Conspicuous proportions of coarsely crystalline calcite commonly are closely associated with the algal fragments. Other components include fragments of skeletons of other organisms, such as bryozoans, crinoids, and brachiopods, and variable proportions of cryptocrystalline carbonate silt. Algal-crust limestone is common in the middle or crystalline limestone subdivision (Harbaugh 1959, p. 302, pl. 6-8) of the thickened Spring Hill Limestone, and also forms a large proportion of the thickened parts of the Captain Creek and Stoner Limestone members. Examples of algal-crust limestone are shown in Plates 2-6 of the present report.

Fragment-Pellet Limestone

Limestone classed as fragment-pellet limestone is composed of poorly sorted fragments of crinoids, sponges, bryozoans, mollusks, brachiopods, fusulinids, and calcareous algae and varying proportions of pellets and carbonate silt. Examples are portrayed in the previous paper (Harbaugh, 1959, p. 301, pl. 5). Proportions of the various organisms also vary, causing limestone of this generalized type to differ in aspect from specimen to specimen. The pellets may be derived in part from calcareous algae, although some pellets consist of clotted aggregates of carbonate silt and may be fecal pellets of mud-ingesting organisms. Fragment-pellet limestone occurs in all limestone members of the Lansing Group in the Wilson-Montgomery County area.

Calcarenite

Limestone classed as calcarenite consists principally of sorted, abraded sand-size particles. The average grain diameters, the proportions of particles derived from different organisms, and the degree of sorting and rounding are variable. Crinoids, brachiopods, fusulinids, bryozoans, sponges, and calcareous algae have been important contributors. Examples are portrayed in Plate 1 of the present report and in Plate 13 of the previous report (Harbaugh, 1959). Calcarenites occur in the upper part of the Spring Hill Limestone and locally in other limestone members.

Breccia Limestone

Limestone classed as breccia limestone consists of coarse angular fragments of previously consolidated carbonate silt. The fragments are contained in a matrix of clear crystalline calcite (Pl. 7). Most fragments have sharp corners, having undergone little or no rounding in the process of being brecciated. In some examples, leaflike algal crusts are closely associated with the breccia fragments (Pl. 7A). Breccia limestone is conspicuous in thickened parts of the Spring Hill, Captain Creek, and Stoner Limestones.

Carbonate Siltstone

Limestone consisting mostly of fine, cryptocrystalline silt-size material may be classed as carbonate siltstone. Limestone

of this type is relatively uncommon in limestones of the Lansing Group in the Wilson-Montgomery County area, but some is present in virtually all Lansing limestones, and it is important locally. Limestone consisting almost wholly of carbonate silt grades into all other limestone types in all degrees.

OÖLITIC LIMESTONE

Limestone consisting of well-sorted oölites forms only a small fraction of the Lansing Group limestones in Wilson and Montgomery Counties, although quantitatively important locally.

TABLE 2.—*Properties of open-space precipitate mosaics contrasted with grain-growth mosaics.*

	Open-space precipitate mosaics	Grain-growth mosaics
Crystal shape	Crystals adjacent to margin of mosaics tend to be elongate. Toward interior of mosaics crystal shape is commonly irregular.	Crystals are very irregular in shape.
Crystal size	Crystals are commonly small near margins of mosaics and progressively increase in size toward centers.	Crystals show no regular variation in size; large and small crystals occur adjacent to each other. Irregular patches of small crystals commonly alternate with patches of larger crystals.
Orientation of crystals	Crystals adjacent to margin of mosaics tend to be oriented perpendicular to margin. Toward center of mosaics, crystals are randomly oriented.	Crystals are oriented at random.
Boundaries of individual crystals	Crystal boundaries commonly are plane or smoothly curved. Where boundaries appear irregular, close scrutiny generally reveals them to be composed of short segments of plane surfaces.	Crystal boundaries are irregularly curved.
Boundaries between mosaics and surrounding sediment	Mosaic-sediment boundaries commonly are sharply defined.	Mosaic-sediment boundaries generally are not sharply defined, although some are sharp.
Presence of inclusions within mosaics	Inclusions are relatively uncommon.	Inclusions of unrecrystallized material are common, adding to the patchy appearance of the mosaic.

FABRIC TYPES

It is now pertinent to consider the types of fabrics in Lansing limestones and to relate these fabrics to rock textures and to development of porosity. Two principal fabric types in Lansing limestones will be considered in this study. One fabric type is represented by crystalline mosaics that have been produced by precipitation of calcium carbonate in open space. These are termed in this report open-space precipitate mosaics or simply precipitate mosaics. The other fabric type is represented by crystalline mosaics produced through recrystallization of fine fragmental material and carbonate silt by grain growth. These mosaics are appropriately termed grain-growth mosaics. The two fabric or mosaic types are usually readily distinguishable from each other because each has distinctive properties. The principal properties of each type are summed up in Table 2, which has been adapted from Bathurst (1958, 1959a, 1959b). Examples of the two types are shown in Plates 1, 3, and 4 and Figures 2 and 4-7.

Development of Open-Space Precipitate Mosaics

It is common observation that elongate crystals that form drusy encrustations through precipitation on the walls of cavities in rocks tend to be oriented more or less perpendicular to the walls. Quartz and calcite crystals are familiar examples. Where an originally existing cavity has been filled, its former presence may be inferred if a crystalline mosaic is present that contains elongate crystals oriented perpendicular to its margins. Good examples of precipitate mosaics containing crystals oriented perpendicular to the walls of former cavities are shown in Plates 1B and 4 and Figures 2B and 7.

The growth of calcite crystals in open space is partly controlled by competition between adjacent crystals (Bathurst, 1959a, p. 374). Crystals having their optic (long) axes oriented more or less perpendicular to the walls of a cavity tend to grow fastest and to grow over and surpass crystals that are not oriented perpendicular to the walls, hence the number of surviving crystals decreases away from the walls. Where adjacent competing crystals touch each other, plane boundaries between them are produced. Adjacent crystal faces join in a line, and where their growth rates are related by a constant, this line

moves in a plane whose orientation is controlled by the relative growth rates of the two crystal faces. The development of plane crystal boundaries is a normal occurrence among competing

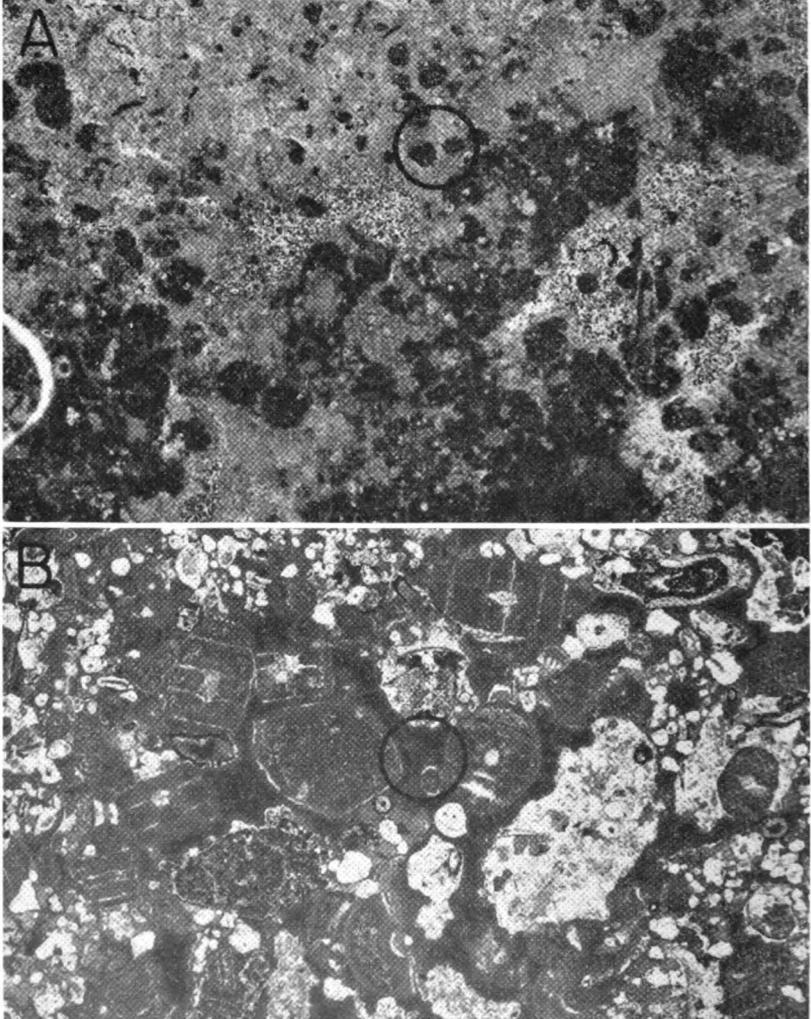PLATE 1. Contrast between grain-growth mosaics and **open-space pre-**cipitate mosaics. Negative peel prints, X 2½. **A.** Patches of **grain-growth** mosaic (dark) in carbonate silt (light). Circle outlines **enlarged view shown** in Figure 2A. Spring Hill member. **B.** Poorly sorted calcarenite **cemented by** crystalline calcite that is an open-space precipitate mosaic. Circle outlines view shown in Figure 2B.
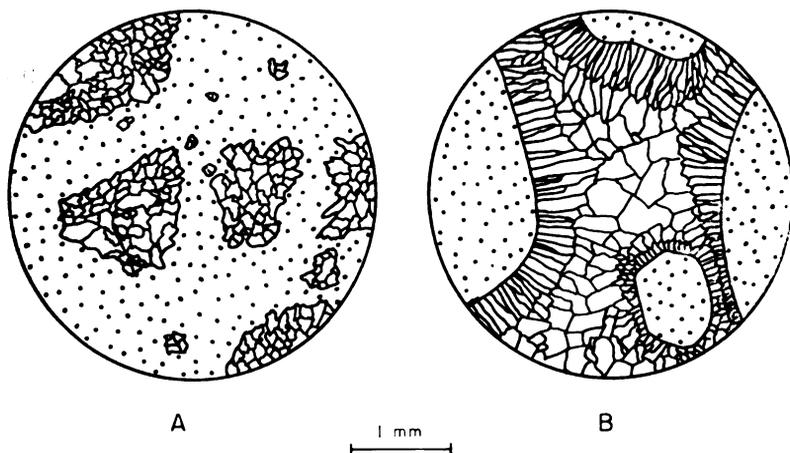
Fig. 2. Contrast between grain-growth mosaics and open-space precipitate mosaics. **A.** Enlarged view of part of specimen in Plate 1A showing patches of grain-growth mosaic in carbonate siltstone (stippled). Note irregular boundaries between individual crystals in mosaic patches. **B.** Enlarged view of part of specimen shown in Plate 1B showing open-space precipitate mosaic occurring as cement between rounded calcarenite particles (stippled).

crystals, whether they have grown by precipitation from solution or by crystallization of a melt, as in metals.

DEVELOPMENT OF GRAIN-GROWTH MOSAICS

Grain-growth mosaics are produced in a radically different manner than open-space precipitate mosaics. Grain growth is a recrystallization process rather than a precipitation process. Bathurst (1959a, p. 375) has pointed out that the name grain growth was given originally by metallurgists to a process of grain enlargement that acts in the solid state. In initially fine grained limestones where the porosity has been sufficiently reduced by cementation or solution transfer of material to provide intimate contact between crystal grains, the boundaries between crystals migrate so that, in general, large grains replace smaller ones and the mosaic gradually becomes coarser. Bathurst (1959a, p. 375) states that the driving force for this replacement is believed to come partly from differences in surface tension across the intercrystalline boundaries and partly from variations in elastic strain between neighboring crystals.

Grain-growth mosaics in limestones are commonly patchy.

The irregular patches shown in Plate 1A are more or less typical. The cause for localization of the individual patches is not well known, although it may be speculated that scattered initially larger crystals serve as "seed" nuclei around which grain-growth recrystallization takes place. Contact of coarsely crystalline precipitate mosaics with carbonate silt also seems to stimulate grain-growth recrystallization of the carbonate silt. The specimen shown in Plates 3 and 4 and Figures 4-7 is a good example of a grain-growth mosaic in contact with a precipitate mosaic.

SOLUTION POROSITY

The pores in outcrop specimens of limestone collected for this study have probably been greatly enlarged and extended in recent geologic time by solution weathering, whereas solution pores in limestones now buried at considerable depths probably have formed in the distant past when they lay at shallow depths beneath ancient erosion surfaces, now represented by unconformities. Taking the uniformitarian view, it seems probable that the processes of pore formation by solution now are similar to those of the past, and that inferences gained from outcrop specimens may be applied with some reservation to buried rocks locally serving as oil-reservoir rocks, despite the large differences in time of development of pores and in other geologic conditions.

Pores in rocks have commonly been classed as either primary or secondary. Primary pores generally form early in the rock's history, either during or shortly after deposition, or may occur later if they are created by fractures. Modifications of pores that take place later are termed secondary. Examples of primary pore spaces include voids between individual crystals, voids between sand- and silt-size particles, voids along bedding planes, voids within a rigid framework provided by calcareous algae, bryozoans, and corals, and voids along joints and other fractures. In carbonate rocks, all these primary openings tend to be subject to modification by solutions, which may be either connate or meteoric waters. As Burgess (1957) has pointed out, the development of secondary porosity is dependent upon the presence of primary pore spaces that permit water to circulate later through the rock or to "gain a toe hold", as he terms it. In the specimens examined in this study it is generally impractical to

attempt to distinguish between primary porosity, secondary porosity formed in the distant past, and secondary porosity formed in geologically recent time.

It has been stated that most secondary porosity in carbonate oil reservoirs is due to solution by meteoric waters (Howard, 1928). The carbonate minerals are not appreciably soluble in pure water, but in weakly acid solutions they are dissolved. According to Imbt (1950), most of the solution action of meteoric waters probably takes place above the water table where meteoric waters are commonly weakly acid, rather than below, where the waters are alkaline and there is a tendency for dissolved calcium carbonate to be precipitated. Acid-charged meteoric waters may move for some distance below the water table before becoming alkaline.

Many pores in carbonate rock exhibit evidence of both solution and deposition. Presumably, solution and deposition can take place almost simultaneously; it would be expected that a solution on the verge of being slightly undersaturated and having power to dissolve might be altered a moment later to slight oversaturation so that deposition takes place. Consequently, the movement of solutions through porous carbonate rocks may result in partial loss of porosity through filling of pores in one place and increase of porosity through enlargement of pores in another place.

Pores observed in outcropping Lansing limestones may be grouped according to mode of occurrence. The principal modes are (1) pores localized along small fractures, (2) pores within precipitate mosaics, (3) pores localized along the contacts of mosaics with carbonate silt or other fragmental material, (4) pores localized within algal crusts, (5) pores localized at the contacts between skeletal particles, and (6) pores produced through dolomitization. These types are described in greater detail on succeeding pages in connection with a discussion of fabric development in various limestone types.

FABRIC AND PORE DEVELOPMENT IN ALGAL-CRUST LIMESTONES

FABRICS

Specimens of algal-crust limestone commonly provide good examples of both open-space precipitate fabric and grain-growth

PLATE 2. Megascopic appearance of algal-crust limestone containing coarsely crystalline open-space precipitate mosaics (dark). Several vugs lined with dolomite crystals occur within open-space precipitate mosaics in central and lower right parts of specimen. Carbonate siltstone (light) forms largest portion of rock. Specimen from crystalline limestone sub-division of Spring Hill member (Harbaugh, 1959). Length of specimen about 8 inches. See Figure 3 for clarification of details. Arrow points to top of bed.
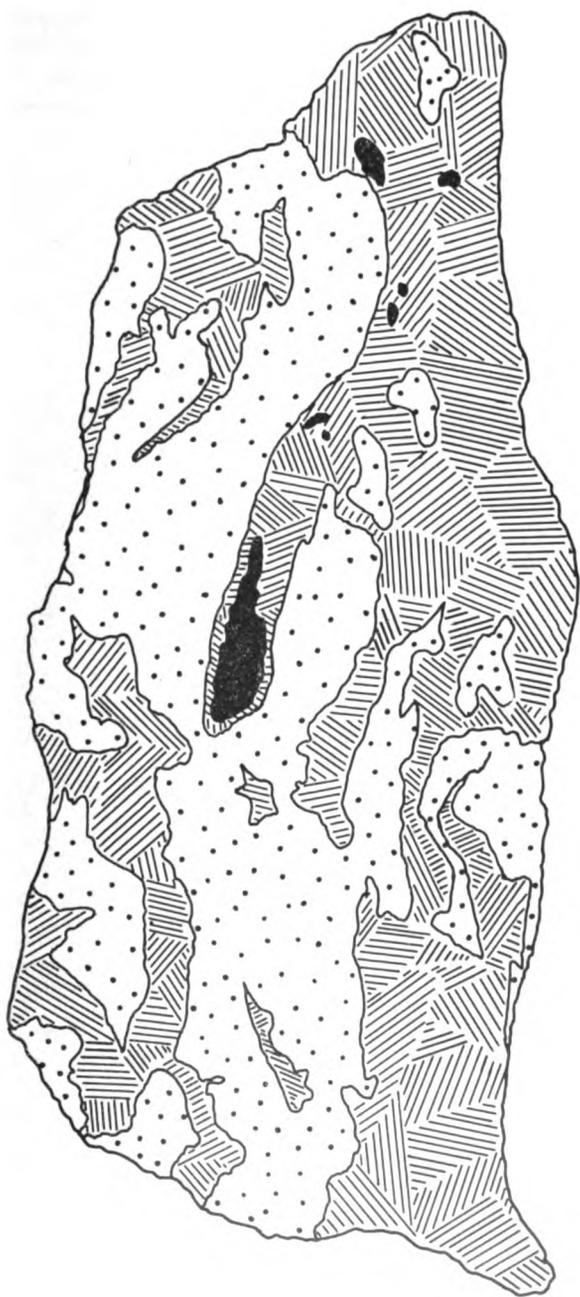
1 inch

FIG. 3. Drawing to accompany Plate 2 showing distribution of open-space precipitate mosaics (irregularly diagonally ruled), carbonate siltstone (stippled), and vugs (black).

fabric. Coarsely crystalline mosaics having open-space precipitate fabric commonly occur adjacent to the undersides of leaflike algal crusts, whereas grain-growth mosaics in turn tend to occur beneath or adjacent to open-space precipitate mosaics. Examples are shown in Plates 2-6 and Figures 3-10.

The close association of precipitate mosaics and algal crusts is simply explained. The crusts have served as miniature "umbrellas", beneath which open spaces (water filled) persisted because of the sheltering effect of the crusts. Fine sediment settling from suspension tended to be caught on the upper surfaces of individual crusts and was prevented from entirely filling the
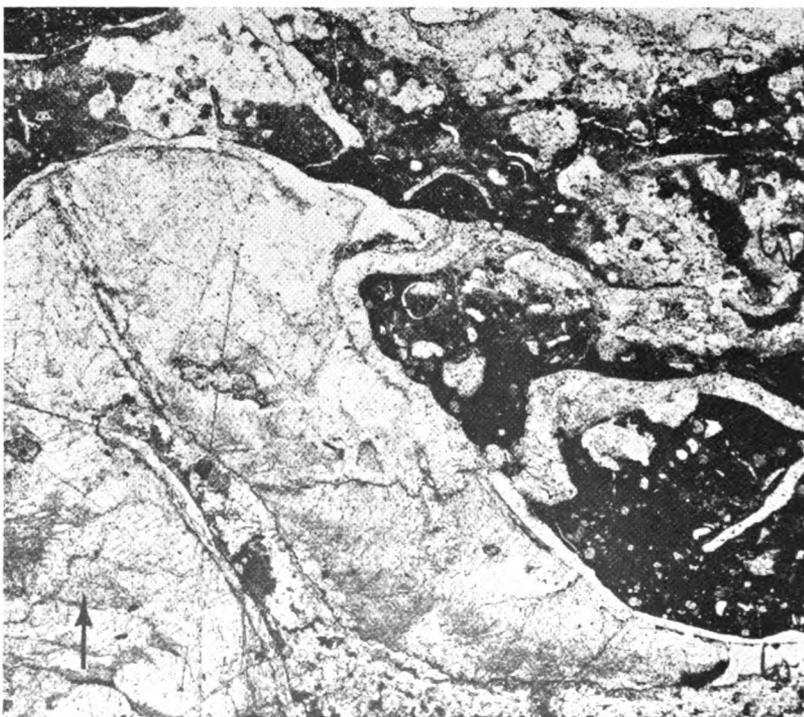
PLATE 3. Open-space precipitate mosaics and grain-growth mosaics associated with algal crusts. Positive print of peel of vertical section, X 3¼. Irregular algal crust extending diagonally across central part of photograph provides sharp separation between carbonate silt (dark) above and open-space precipitate mosaic (light) below. Mottled light grain-growth mosaic in lower part of photograph separates precipitate mosaic from second algal crust below, part of which is shown in photograph. See Figure 4 for clarification of details. Arrow points to top of bed. Specimen from middle subdivision of Spring Hill member.

spaces beneath the crusts. The open spaces were subsequently filled with mosaics of precipitated calcium carbonate. The outlines of the mosaics reflect the shapes of the original open spaces, which were governed by the shape of algal crusts as well as by the attitudes of individual crusts in respect to each other. The specimen shown in Plates 3 and 4 and Figures 4 and 6 contains a coarsely crystalline precipitate mosaic adjacent to the underside of a very irregular algal crust. Carbonate silt above an algal crust in the lower part of this specimen and below the large precipitate mosaic (Pl. 3, Fig. 4) has undergone partial grain-growth recrystallization. Both mosaics exhibit typical fabric features (Fig. 5, 7).

The examples shown in Plates 5A and 6 and Figures 8-10 il-

I cm

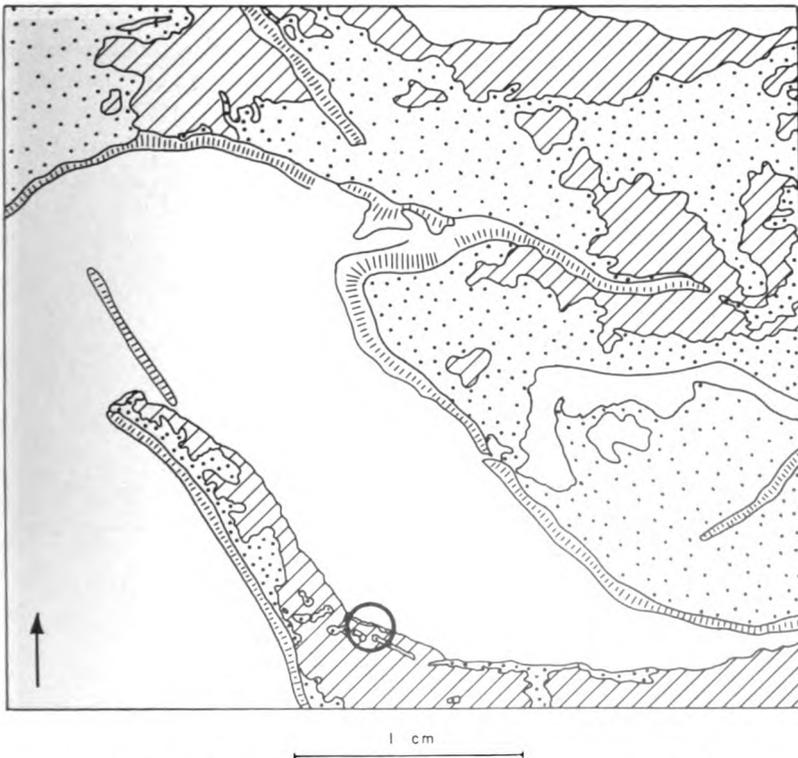Fɪɢ. 4. Drawing to accompany Plate 3 showing relations of fabric types to algal crusts. Grain-growth mosaic is diagonally ruled, open-space precipitate mosaic is clear, carbonate siltstone is stippled, and algal crusts are hachured. Circle outlines enlarged view shown in Figure 5.

lustrate the variety of cross-section shapes that precipitate mosaics may assume where associated with algal crusts. Those of Plate 5A and Figure 8 are crudely triangular in section, conforming to the configuration of curving algal crusts that touch each other somewhat like sloping rafters. Those of Plate 6 and Figures 9 and 10 illustrate the complex shapes of the precipitate mosaics associated with diversely oriented irregular segments of algal crusts. The lower surfaces of the mosaics are more nearly horizontal than the upper surfaces, indicating that the lower surfaces are in contact with carbonate silt or fine fragmental material, which tended to accumulate in more nearly horizontal layers.

Pores

Pore spaces in algal-crust limestone are formed under a variety of circumstances but two modes of occurrence are most notable. Pores are particularly abundant (1) in the open-space precipitate mosaics and (2) in spaces formerly occupied by algal crusts. Good examples of large pores occurring within precipitate mosaics are shown in Plates 2 and 4 and Figures 3 and 6. These large pores may have been produced chiefly through solution of calcite by ground water or they may represent in part pores that

| | 1 mm | |
| A | ⊢————————⊣ | B |
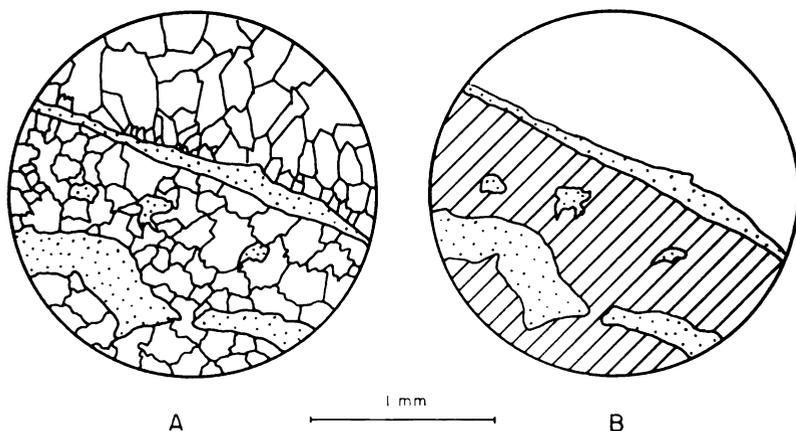
Fig. 5. Enlarged view of contact between open-space precipitate mosaic and grain-growth mosaic shown in encircled area of Figure 4. A shows crystal shapes, B is key, distinguishing grain-growth mosaics (diagonally ruled), open-space precipitate mosaics (clear), and carbonate siltstone (stippled). Note irregular intercrystal boundaries in grain-growth mosaic as contrasted to more nearly plane boundaries in precipitate mosaic.

PLATE 4. Horizontal section through same specimen shown in Plate 3. Note that peel print is negative rather than positive. Shows association of vug or large pore (black) with coarse crystalline mosaics. Other smaller pores are associated with locally dolomitized patches. See Figure 6 for clarification of details; X 3¼.

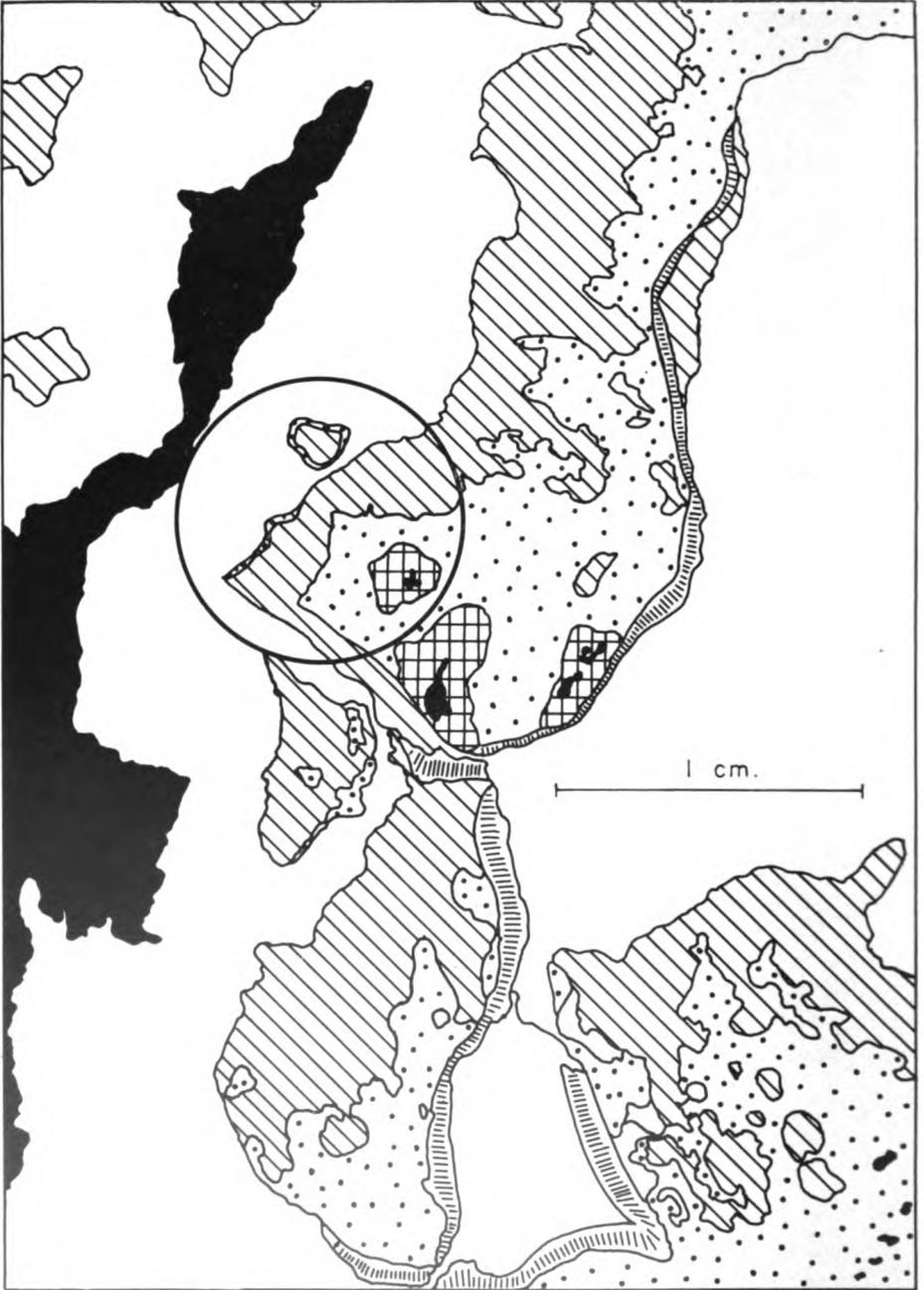Fig. 6. Drawing to accompany Plate 4 showing relations of **vugs, fabric types, and algal crusts.** Vugs are black, open-space precipitate mosaics **are clear, grain-growth** mosaics are diagonally ruled, dolomitized parts are cross-hatched, **algal crusts are** hachured, and carbonate siltstone is stippled. Circle outlines **enlarged view shown in** Figure 7.

have persisted since the rock was formed. Murray (1960, p. 66) has illustrated an example of a limestone rich in leaflike algal crusts in which pores seem to have formed as a result of incomplete filling between the crusts and to have persisted with little modification since deposition of the limestone. The pores localized within many precipitate mosaics thus may result from solution enlargement of smaller pores that remained as a result of incomplete filling of the original open spaces.

The presence of pores within sites formerly occupied by algal crusts (Pl. 5B) also is probably due to enlargement of small primary pores that remained inside the crusts as a result of incomplete filling with calcium carbonate. Where the crusts are preserved, they show fabric features typical of precipitation in open space.

Comparison of Mosaics with Stromatactis

Precipitate mosaics in algal-crust limestone are similar in some respects to the sedimentary structures that have been likened to Stromatactis. DuPont (1881) gave the name Stromatactis to mosaics of coarse crystalline calcite in Devonian limestones of the Ardennes in Belgium, in allusion to the pos-

A   5 mm   B

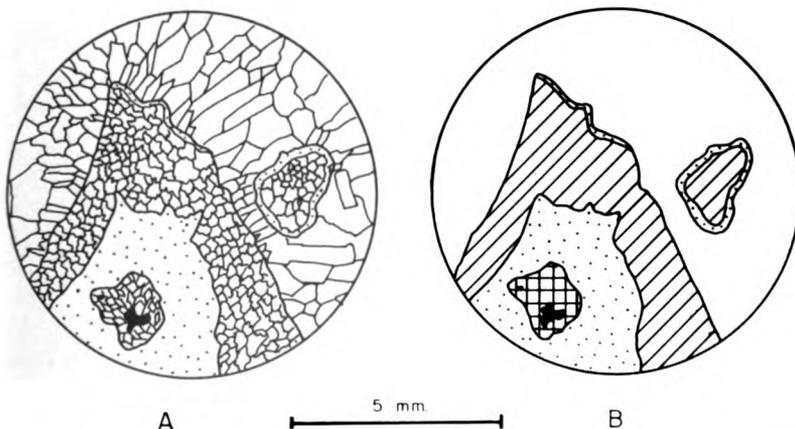Fig. 7. Enlarged view of encircled area shown in Figure 6. **A** shows crystal shapes. **B** is key to open-space precipitate mosaic (clear), grain-growth mosaic (diagonally ruled), dolomitized patch (cross hatched), pores (black), and unrecrystallized carbonate siltstone (stippled). Note rims of unrecrystallized carbonate siltstone, which locally separate precipitate mosaic from grain-growth mosaic.

| 1 cm. |

Fig. 8. Drawing to accompany Plate 5A showing relations of algal crusts (hachured), open-space precipitate mosaics (clear), and carbonate siltstone (stippled).

sibility that the mosaics might represent a kind of reef-building stromatoporoid. Although the question of organic versus inorganic ultimate origin of the Belgian examples remains unsettled (Lecompte, 1937), most geologists who presently employ the term Stromatactis use it as a sedimentary structural term and not as a name of an organism.

PLATE 5. Algal-crust limestones of Captain Creek member containing numerous irregularly curving leaflike algal crusts. Carbonate siltstone is aggregated into pellets locally. Arrows point to top of bed. Negative peel prints; X 3½. **A.** Coarse open-space precipitate mosaics adjacent to undersides of algal crusts. Mosaics commonly have triangular outline where they form beneath two crusts that touch each other. See Figure 8 for clarification of details. **B.** Solution pores occupy sites formerly occupied by curving algal crusts.
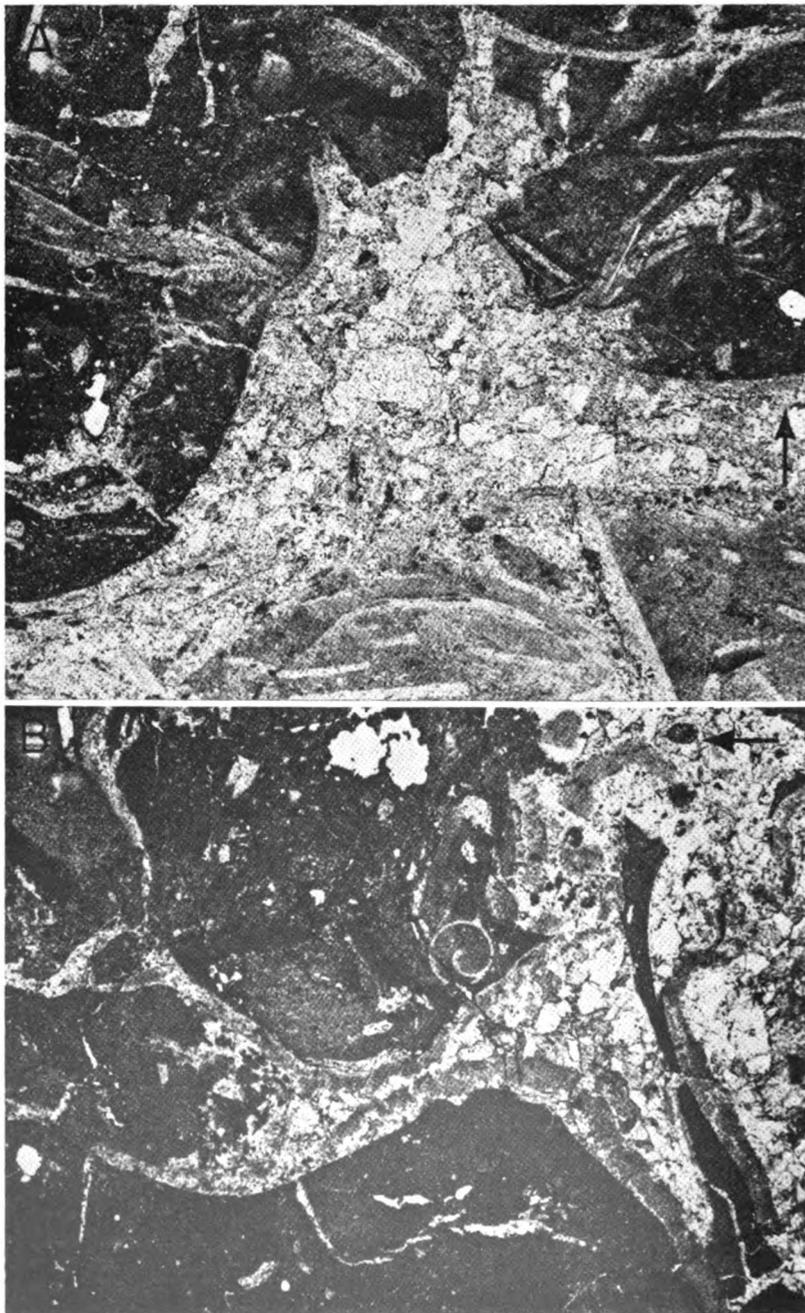
I cm.

FIG. 9. Drawing to accompany Plate 6A showing relations of algal crusts (hachured), open-space precipitate mosaic (clear), grain-growth mosaic (diagonally ruled), and carbonate siltstone (stippled).

The Stromatactis mosaics described by Bathurst (1959b) are open-space precipitates that have filled irregular cavities. In general, the mosaics have smooth and more or less horizontal lower surfaces but have intricately shaped upper surfaces. Presumably, the outlines of the mosaics represent the outlines of the original cavities. In examples illustrated by Bathurst, the mosaics are completely surrounded by carbonate silt, although the lower surfaces of the mosaics are in contact with secondary

PLATE 6. Irregular shapes of open-space precipitate mosaics associated with algal crusts. Note that prints are positive rather than negative; X 3. Precipitate mosaics and algal crusts are light, carbonate siltstone is darker. Captain Creek member. Arrows point to top of bed. A. Irregular precipitate mosaic formed beneath algal crust fragments. Note that crust fragments seem to have been incorporated into coarsely crystalline mosaic in some places and not in others. See Figure 9 for clarification of details. B. Precipitate mosaics formed adjacent to both sides of irregularly curving crusts. See Figure 10 for clarification of details.
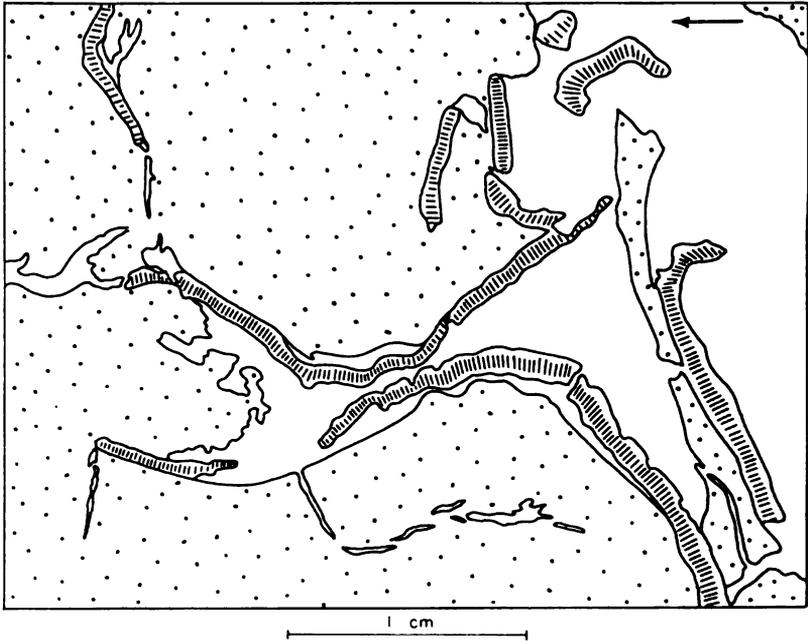
Fig. 10. Drawing to accompany Plate 6B showing relations of algal crusts (hachured), open–space precipitate mosaic (clear), and carbonate siltstone (stippled).

carbonate silt, which partly filled the lower parts of cavities before final filling with precipitated calcium carbonate. No wholly satisfactory explanation of origin of the cavities has been devised. Bathurst suggests that the cavities may possibly have formed through decay of soft-bodied organisms originally buried in the carbonate silt, or that internal erosion of semi-consolidated carbonate silt may have produced interconnected cavities.

The similarities and differences between precipitate mosaics in Lansing algal-crust limestones and the Stromatactis mosaics of English knoll-reefs described by Bathurst are summed up in Table 3 and compared graphically in Figure 11. It is suggested that the umbrella effect of algal crusts, illustrated by Lansing limestones, be considered as an additional mode of origin of cavities now filled with Stromatactis-like forms in certain other limestones. Admittedly, however, this explanation is not everywhere applicable, especially where there is no evidence of the former presence of algal crusts, as in the limestones described by Bathurst.

A
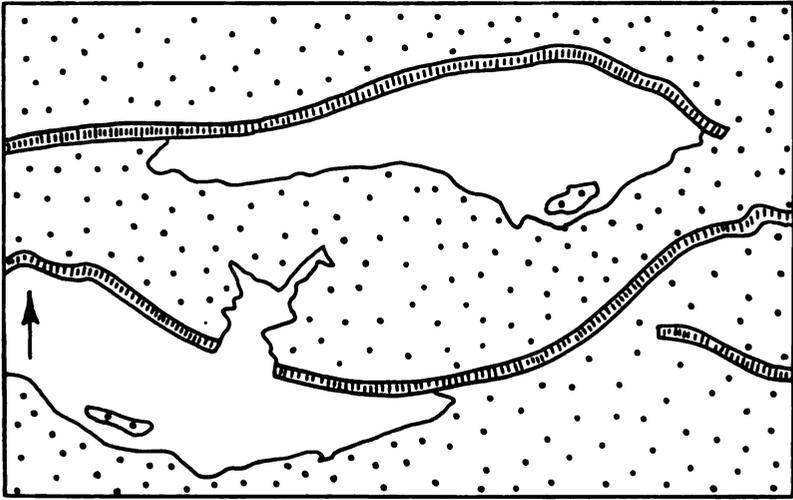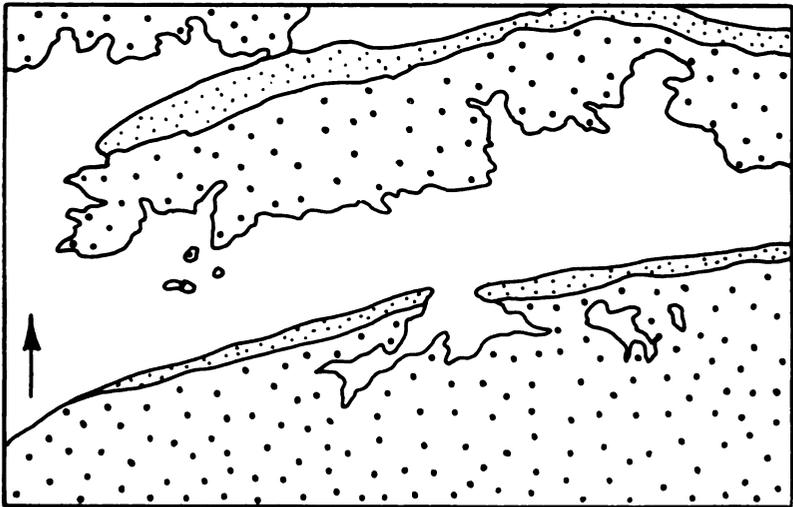
B |⎯⎯⎯⎯⎯⎯⎯⎯⎯⎯⎯⎯⎯| I cm.

FIG. 11. Contrast between precipitate mosaics in Lansing limestones (A) and Stromatactis-type mosaics (B) in English knoll-reef limestones described by Bathurst (1959b, pl. 1A, fig. 1). Drawings are generalized. Open-space precipitate is clear, carbonate siltstone is coarse stippled, algal crusts are hachured, and secondary or internal sediments are fine stippled. Arrows point to top of beds. Note that upper surface of Stromatactis-type mosaic is more irregular than mosaics in Lansing limestones.

TABLE 3.—*Comparison of Lansing precipitate mosaics with Stromatactis mosaics.*

	Lansing algal-crust limestones	Stromatactis mosaics in English knoll-reef limestones described by Bathurst (1959b)
Dimensions of mosaics	Dimensions variable, width ranging generally from 1 to 5 mm and lengths to 10 cm.	Dimensions same order of magnitude as in Lansing limestones.
Upper surface of mosaics	Upper surface in contact with algal crusts. Contact is curving, but not notably irregular. Appendix-like projections occur locally, however.	Upper surface in contact with carbonate silt. Contact is digitate and generally complex.
Lower surface of mosaics	Lower surface in contact with carbonate silt. Contact is gently undulating and rudely parallel with bedding.	Lower surface in contact with internal (secondary) carbonate silt that previously partly filled cavity. Contact is gently undulating and rudely parallel with bedding.
Crystal orientation	Elongate crystals oriented perpendicular to boundaries of mosaics. Toward center of mosaics, crystals have random orientation.	Orientation essentially same as in Lansing limestones.

FABRIC AND PORE DEVELOPMENT IN SEDIMENTARY BRECCIAS

FABRICS

The clear crystalline mosaics of Lansing sedimentary breccias (Pl. 7, Fig. 12 and 13) have fabrics typical of precipitation in open space. The intercrystalline boundaries are plane, and small crystals are oriented perpendicular to the margins of the mosaics.

The sedimentary breccias seem to have been formed by breaking up of aggregates of carbonate silt that were previously sufficiently consolidated to permit them to be held together. It is speculated that algal filaments may have permeated the silt,

PLATE 7. Breccia limestones composed of sharp-edged fragments of carbonate siltstone (light) in a matrix of clear precipitate-mosaic calcite (dark). Carbonate siltstone is aggregated into irregular pellets of various sizes. Arrows point to top of beds. Negative peel prints. **A.** Lower surfaces of carbonate siltstone fragments are associated with algal crusts. Spring Hill member. See Figures 12-14 for clarification of details; X 1 3/4. **B.** Breccia composed of thin blocky fragments. Most pores (black) are localized in sites formerly occupied by crystalline matrix. Captain Creek member. See Figure 15 for clarification of details; X 3 3/4.
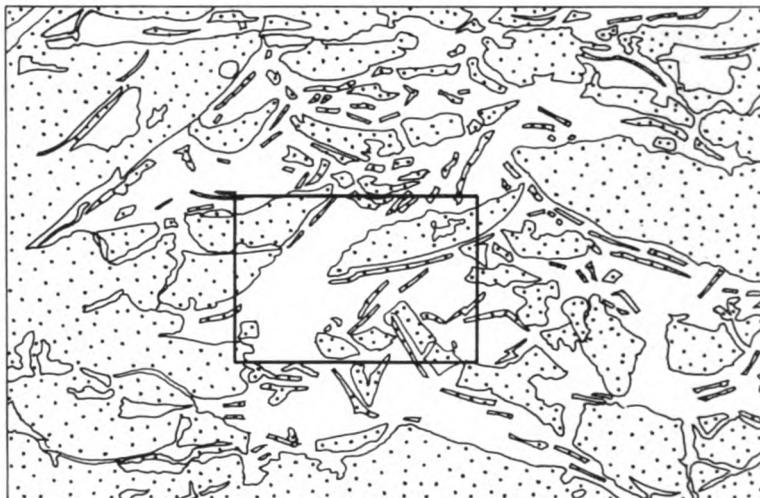
FIG. 12. Drawing to accompany Plate 7A. Carbonate siltstone is stippled and matrix of precipitate mosaic is clear. Rectangle outlines enlarged view shown in Figure 13.
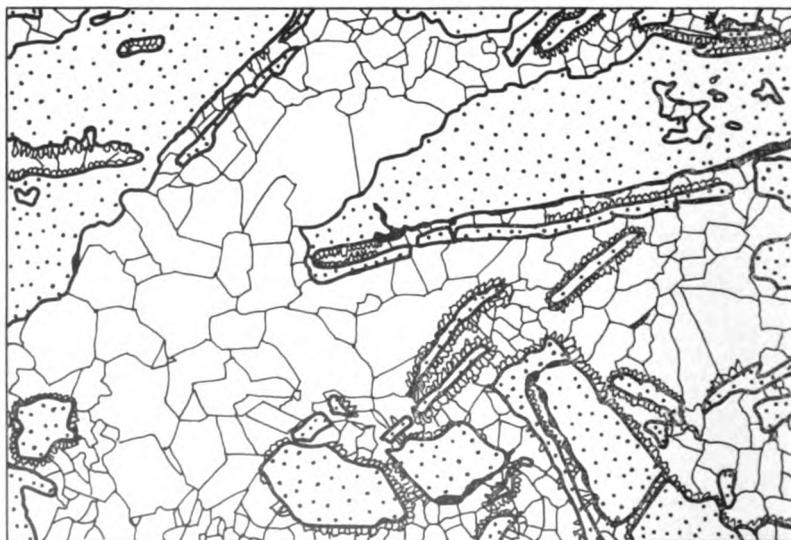

FIG. 13. Enlarged view of area outlined in Figure 12. **Carbonate siltstone** is stippled. Individual crystals within precipitate-mosaic **matrix are shown.** Small pores are shown with broader black lines.

I cm
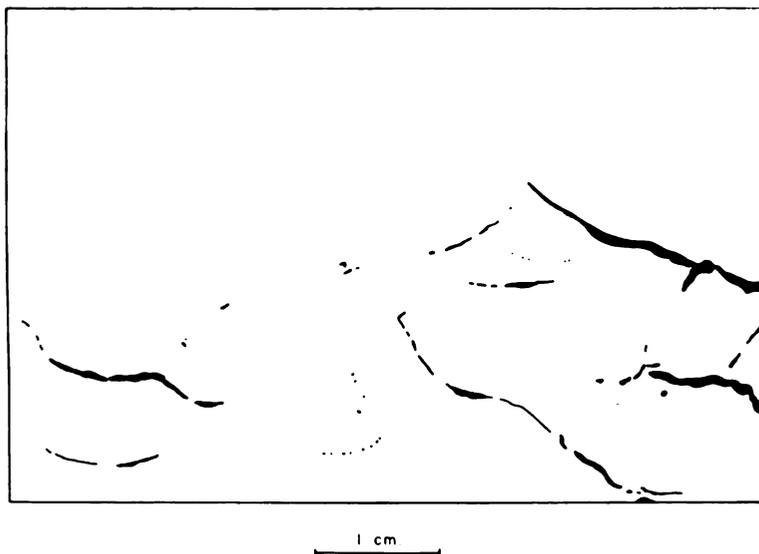
FIG. 14. Drawing to accompany Plate 7A showing outlines of pores. Note that pores are localized along boundaries between carbonate siltstone fragments and crystalline matrix.

exerting a consolidating effect. A large proportion of open space was produced in the process of breaking up, which was followed by filling of the space through precipitation.

PORES

Two modes of pore occurrence are exhibited by specimens illustrated in Plate 7. In one specimen (Pl. 7A, Fig. 12-14) the pores are localized along the boundaries between the crystalline mosaic matrix and fragments of carbonate silt. In the other specimen, the pores seem mostly to occupy spaces formerly occupied by clear mosaic between breccia fragments. It seems probable that incomplete filling of the spaces between breccia fragments left small pores that were later greatly enlarged by solution.

FABRIC AND PORE DEVELOPMENT IN CALCARENITES AND OOLITES

Well-sorted calcarenites and oölites are commonly cemented with clear calcite that exhibits a fabric typical of precipitation in open space. An example is shown in Plate 1B and Figure 2B. An additional fabric type of minor importance in Lansing lime-

I   cm.
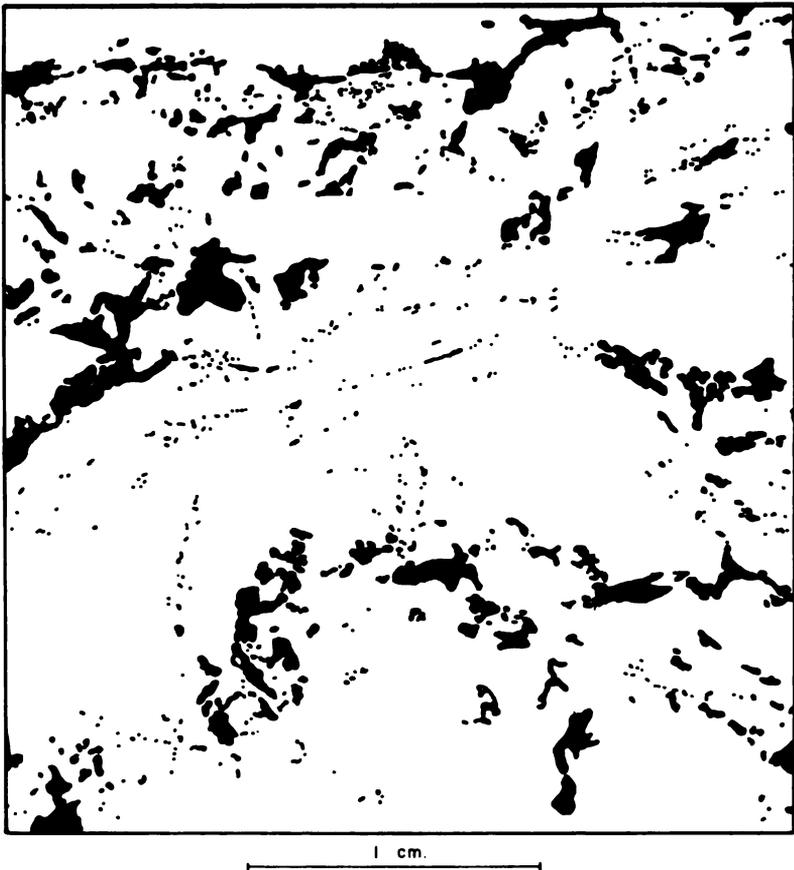
FIG. 15. Drawing to accompany Plate 7B showing outlines of pores. Note that pores occupy sites formerly occupied by coarse crystalline matrix.

stones and not heretofore discussed in this paper also occurs, and is termed rim cementation. In rim cementation, a rim is added or cemented to a clastic particle, which is a single crystal. Many crinoid fragments, for example, are single crystals. The rim is formed in crystal lattice continuity with the clastic particle, thus creating a larger crystal (Bathurst, 1958, p. 21).

Pores in calcarenites and oölites are localized to some extent within the clear calcite cement. It seems probable that incomplete filling of the original intergranular spaces by cement left pores that were later enlarged by solution.

OTHER FACTORS AFFECTING PORE DEVELOPMENT

Other factors that localize pore development are fractures, bedding planes, dolomitized parts of the rock, and contacts between skeletal particles. Both large and small fractures have had important influence. It is probable that many pores whose localization seems to be random are actually controlled by fractures that are either too small to be seen or that do not intersect the plane of the peel. An example of a fracture-controlled pore is shown in Plate 5A. Here the fracture extends more or less vertically and is shown in the left-central part of the photograph.

Pores are localized at the contacts between skeletal particles or layers and between skeletal particles and carbonate silt matrix. An example is shown in Plate 8A, where an elongate chain of pores is localized along encrusted fractures that irregularly intersect carbonate silt and various skeletal particles. Pores are also localized along bedding planes and between layers of unlike lithology. Plate 8B shows an example of pores localized at the boundary separating fragment-pellet limestone below and carbonate siltstone above. Finally, pores are localized within dolomitized patches. An example is shown in Plate 4 and Figures 6 and 7.

DEPOSITIONAL ENVIRONMENT OF LANSING LIMESTONES

Interpretation of depositional environments requires consideration of both small- and large-scale features. Small-scale features of Lansing limestones have been interpreted previously in this paper and it is now appropriate to consider the general, large-scale features that bear on depositional environment of the limestones in the Wilson-Montgomery County area. These large-scale features are itemized below:

a. Algal-crust limestone and breccia limestone occur principally in thickened parts of the Spring Hill, Captain Creek, and Stoner members.

b. Large variations in thickness occur in all members of the Lansing Group except the Merriam Limestone of the Lansing Group (Fig. 17).

c. In places, abnormally thick limestone members are overlain by abnormally thin shales. For example, where the Spring Hill Limestone member is thick, the overlying Vilas Shale generally is thin (Harbaugh, 1959, pl. 1).
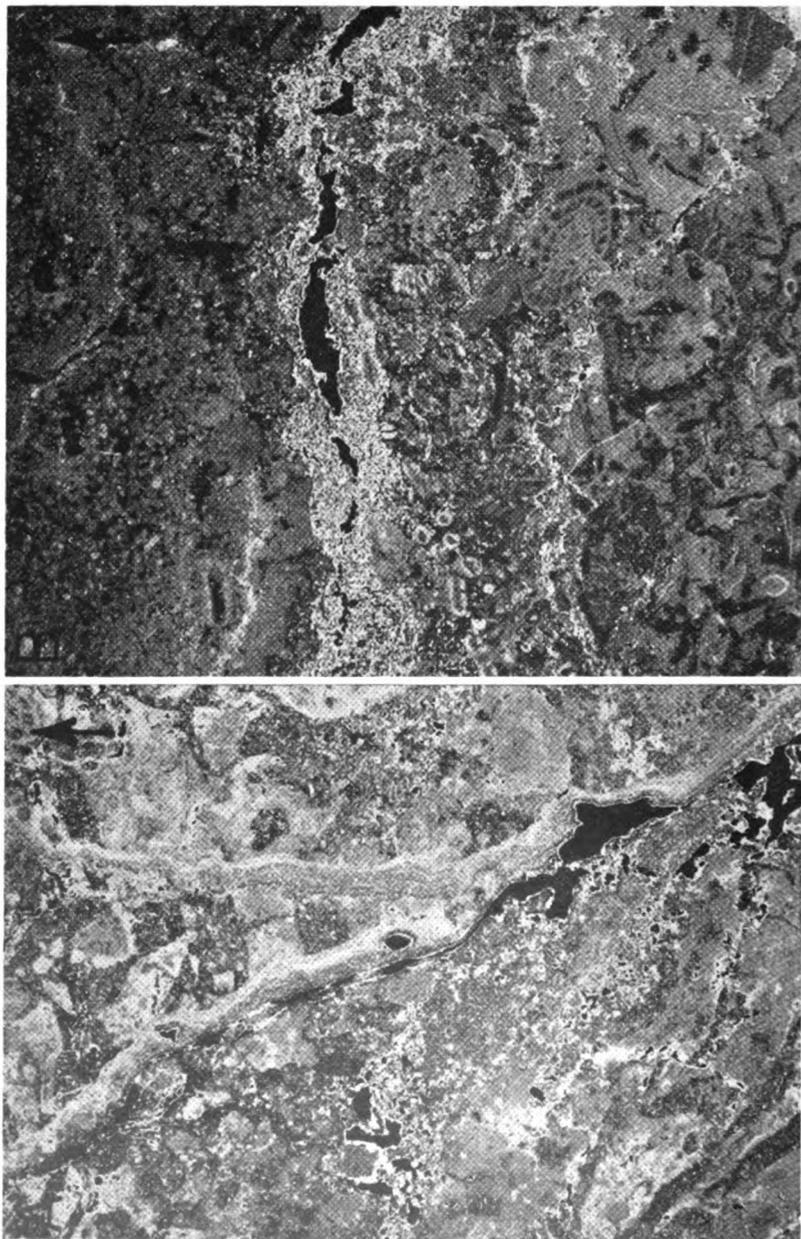
PLATE 8. Localization of solution pores by lithologic features. South Bend member. Negative print; X 5. A. Elongate pores along encrusted fractures. B. Elongate pores along boundary between clotted carbonate silt above and fragment-pellet limestone below.

d. Thickness variations in the Captain Creek, Stoner, and South Bend Limestone members more or less parallel each other. All thicken abnormally in the same general localities (Fig. 17 and 18).

e. Oölites and more or less homogeneous carbonate siltstones occur principally south of the mid-latitude of Township 32 South (Fig. 19).

With these general observations in mind, plus observations of microscopic characteristics, it is feasible to draw the following general conclusions concerning origin and depositional environment of the Lansing limestones:

1. Thickened portions of Lansing limestones probably represent deposits formed on marine banks that rose above the general level of the surrounding sea floor. Evidence for this conclusion includes the presence of large-scale cross-beds (Hickory Creek member), which imply depositional slopes and therefore relief on the sea floor (Harbaugh, 1959). The relief and areal extent of these marine banks varied widely. The large bank represented by the Plattsburg Limestone in the Neodesha-Fredonia area (Harbaugh, 1959, pl. 1) extended over at least 150 square miles and at times probably rose several tens of feet above the surrounding sea floor. Banks represented by thickened parts of the Captain Creek, Stoner, and South Bend members were less extensive areally (Fig. 17 and 18), although they may have had a relief as great as that of the Plattsburg bank. The locations of measured sections from which thickness information has been derived are shown in Figure 16. The thickened limestone bodies probably should not be regarded as wave-resistant reefs, because they show little evidence of frame-building organisms.

The tendency of thickness variations in a limestone member to be inversely related to thickness variations in the overlying shale member seems to be due to partial lateral gradation of lithologies. Part of the Plattsburg Limestone has been interpreted as having been deposited at the same time as the Vilas Shale (Chelikowsky and Burgat, 1947; Newell, 1933), and Harbaugh (1959) has suggested that differences in sea floor elevation dictated whether limestone (shallow) or shale (deeper) was deposited.

2. Currents probably were important factors in controlling height and areal extent of banks, particularly those containing
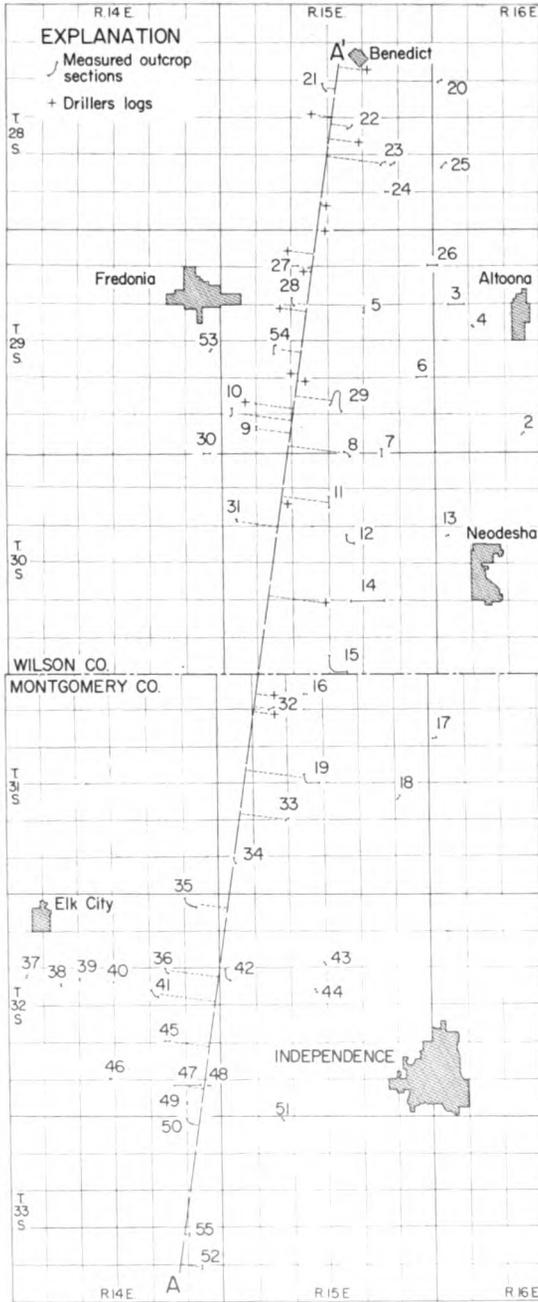
abundant algal crusts. Examination of algal-crust limestones reveals that most of the leaflike crusts have been fragmented. This in turn suggests that few of the crusts are in position of growth and that most of them have been transported by currents. It seems possible that accumulation of algal crusts on the banks was due in part to concentration by currents, which may have swept the crusts from a large area and deposited them on the banks. It is probable, however, that growth of the algae also was encouraged over the banks, because of shallower water and greater light intensity.

The modern alga *Halimeda* may provide a rough analogue to the leaflike algal crusts of the Lansing limestones. *Halimeda* is a branching, jointed alga that is widespread in warm modern seas and is also represented in many Tertiary limestones. Johnson (1957, p. 178) provides a good description of the growth habits of *Halimeda* of Saipan, where *Halimeda* occurs in fossil form as a limestone maker and in living form in abundance on submerged flats of some of the fringing reefs and in the lagoon areas.

Part of Johnson's description of *Halimeda* is quoted below: "*Halimeda* occur in great numbers locally. They grow attached to the bottom as small bushy plants several inches high. Each bush is composed of many branches or fronds, each of which is segmented. Many of the segments resemble small models of the prickly pear (*Opuntia*) leaf. The young and growing forms are bright green. As they grow older, they become more and more encrusted with lime and assume a grayish appearance. After the death of the plant, the branches tend to break into separate fragments which bleach white or gray."

The Lansing algal crust fragments may have behaved similarly, for destruction of the algal plants after death seems to have been the general rule, just as in the modern *Halimeda*.

The distribution of *Halimeda* fragments following death of individual plants likewise may provide an analogy. Cloud and others (1956, p. 81) have described the effects of currents on *Halimeda* fragments at Saipan. They state ". . . . direct observa-

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FIG. 16. Map showing location of measured sections used in cross section (Fig. 17) and thickness maps (Fig. 18). Measured sections 27, 28, 29, and 54 from Wagner and Harris (1953); other sections measured by author, although some represent remeasurements of measured sections by Davis (1959), Wilson (1957), Eastwood (1958), and unpublished measured sections in files of State Geological Survey of Kansas and of State Highway Commission of Kansas.

tions of the bottom sediments off western Saipan reveal that the freshly detached joints of *Halimeda* are in large proportion only partly calcified and tend to be relatively light and porous. They settle in the areas of growth of *Halimeda* as loosely knit debris which is readily moved about by current action. The broadest areas of seemingly thick accumulation of *Halimeda* joints on the present bottom are at the harbor entrance, where they seemingly have been concentrated by winnowing action of the out-flowing current. Such winnowing may move the relatively light and buoyant *Halimeda* fragments seaward from the denser, coarse shell and coral debris that accumulates in shallower inshore waters, while carrying to still deeper seaward waters that part

South Bend Limestone member
and
Rock Lake Shale member
undifferentiated

Stoner Limestone
member

STANTON LIMESTONE

Eudora Shale
member

Captain Creek Limestone
member

VILAS SHALE

PLATTSBURG LIMESTONE
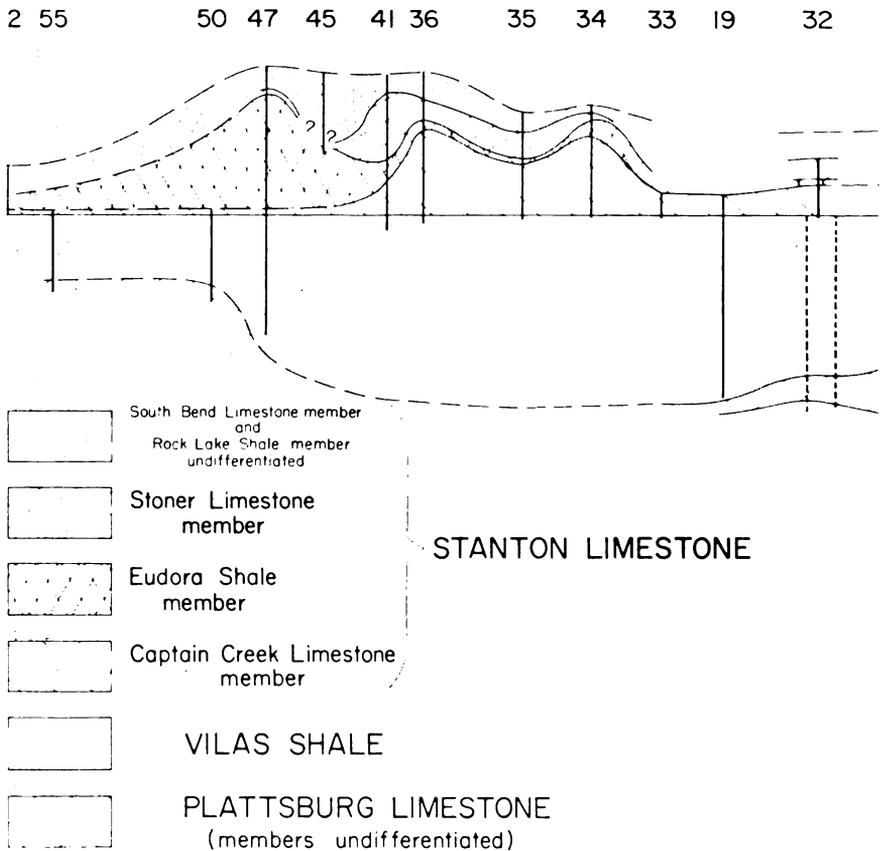(members undifferentiated)

Fig. 17. Geologic cross section showing thickness variations in divisions of Lansing Group in Wilson-Montgomery County area. Base of Captain Creek member

of the concurrently moving fine debris that does not settle into the interspaces between the *Halimeda* particles."

3. The upper surfaces of the banks probably lay close to the surface of the sea and may have been exposed intermittently. Evidence suggesting this interpretation is provided by the breccia limestones and also by the large proportion of calcite of open-space precipitate mosaic in algal-crust limestones.

The breccia limestones resemble to a considerable extent the breccias that form on intermittently subaerially exposed mud flats in areas of carbonate deposition. Ginsburg and others (1954) have described mud flat breccias in Florida Bay, which form within or slightly above the intertidal zone. They stress the im-

31 11   8 9 10 29   54   28 27   23 22 21
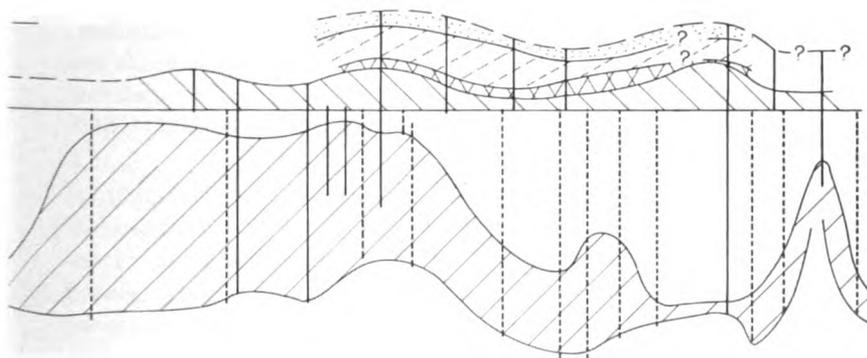
Contact between stratigraphic units where relations are relatively better known	Contact between stratigraphic units where relations are relatively poorly known	FEET 100
28		Vertical scale exaggerated 75 times
Locality number and vertical extent of measured outcrop	Drillers log (thickness intervals shown here confined to Vilas Shale and Plattsburg Limestone)	50 MILES 0 1 2 3 Horizontal Scale
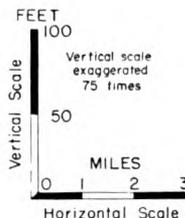
has been plotted as arbitrary horizontal datum. Numbers denote measured sections shown in Figure 16, which also shows line of cross section.

portance of algae in binding the mud and silt-size carbonate particles together to produce a laminated, stromatolite-like sediment. Brecciation of the sediment is due to shrinkage when the mud flats dry out after extended subaerial exposure. It seems possible that the Lansing breccia limestones were formed under analogous conditions.

Studies of modern carbonate deposits indicate that the filling of open spaces by precipitation of calcium carbonate may take place close to sea level. The open-space precipitate mosaics of Lansing algal-crust limestones and breccia limestones likewise may have been formed close to sea level. Newell (1955, p. 303) discusses the conditions under which calcium carbonate is precipitated in cavities at Raroia Atoll. At the reef front at Raroia Atoll, open spaces form an estimated 25 to 50 percent of the volume of the rock and at the reef rim the proportion of open space is even greater. These open spaces are formed where successive generations of corals and calcareous algae accumulate, leaving voids between and within their skeletons. The voids are not completely sealed and tend to be filled with bioclastic detritus and with inorganic deposits of fibrous calcium carbonate, which in this case consists of aragonite.

Newell has interpreted Cullis' description (1904, p. 399) of the cores taken at Funafuti Atoll, pointing out that at Funafuti the reef detritus had entered cavities after precipitation of encrusting layers of calcium carbonate. This relationship suggested to Newell that chemical precipitates as well as detrital material (carbonate silt) were deposited while the voids were still in free communication with the sea.

Newell also describes cementation taking place in coarse calcareous detritus in the reef flat at Raroia Atoll, where the interstices between originally unconsolidated grains are being filled with fibrous aragonite in a manner perhaps similar to that in the voids in reef limestones at Funafuti. The Raroia reef-flat detrital limestone is now slightly above sea level. Its position near sea level suggests recent age and deposition of fibrous aragonite cement near sea level. Emery and others (1954, p. 148) conclude that cementation takes place at or below low tide level at Bikini, and Ginsburg (1957, p. 95) argues for cementation of calcareous beachrock in Florida through exposure to meteoric waters at or above sea level.

Newell (1955, p. 304) stated that the calcium carbonate deposited early in primary pores of reef limestones is derived from near-surface sea waters, which tend to be supersaturated with calcium carbonate because they are warmed in the daytime over shallow reef flats, and because of photosynthesis by reef plants. During ebb tides, reef-flat waters are elevated a few inches above the surrounding sea, creating a weak hydrostatic head, which encourages the water to escape seaward by sinking through myriads of pores within the reef flat. Calcium carbonate is probably precipitated in transit.

4. The transition of relatively thick limestones to thin limestones in a predominantly shale sequence south of the mid-latitude of T. 32 S. represents a fundamental change in depositional environment. Most of the units in the Kansas Pennsylvanian exhibit similar facies changes near this general latitude, creating considerable confusion in tracing stratigraphic units southward into Oklahoma. The increase in proportion of shale and sandstone suggests that source areas of terrigenous clastics lay in a generally southerly direction.

A large proportion of the limestones south of T. 32 S. is oölitic, although some homogenous carbonate siltstones and some calcarenites occur. The presence of oölitic limestone suggests deposition in very shallow water in which evaporation and warming helped bring about supersaturation and consequent precipitation. The calcarenites are composed of sorted, rounded particles, which would also seem to be formed readily in shallow, agitated waters. Locally, the oölitic limestones are cross bedded (as northeast of Tyro, in sec. 20, T. 34 S., R. 15 E.) and may represent submarine oölite bars similar to the underwater calcareous bars of the Great Bahama Bank. Wilson (1957) interpreted the oölitic limestones and thickened shales south of T. 32 S. as lagoonal deposits, an interpretation that seems reasonable if the lagoons were very shallow.

5. The geographic relations between currents, sources of terrigenous sediments, shoal areas, banks, and deeper water areas probably remained more or less unchanged during the time required for deposition of the Captain Creek, Stoner, and South Bend Limestones in the limited area of this study. This interpretation is suggested by the fact that each of these limestones is thickened in the same general locality. (Fig. 18).

Figure 19 is a hypothetical graphic interpretation of the generalized geographic relations that prevailed during deposition of the Captain Creek or the Stoner Limestones. South of T. 32 S. oölites and calcarenites were deposited in shallow lagoons or over shallow shoals and were heaped into bars in places. Toward the north, fragmented algal crusts and skeletal debris accumulated in banks and to a lesser extent in deeper water. An irregular channel has been shown on the speculation that streams flowing northward from a distant terrigenous source area farther south or southeast entered the sea in scour channels that meandered across the broad shallow shoals. Wilson (1957, p. 433) points out that certain sandstones of the Rock Lake Shale member resemble deltaic or channel sandstones, which would seem to support this point.
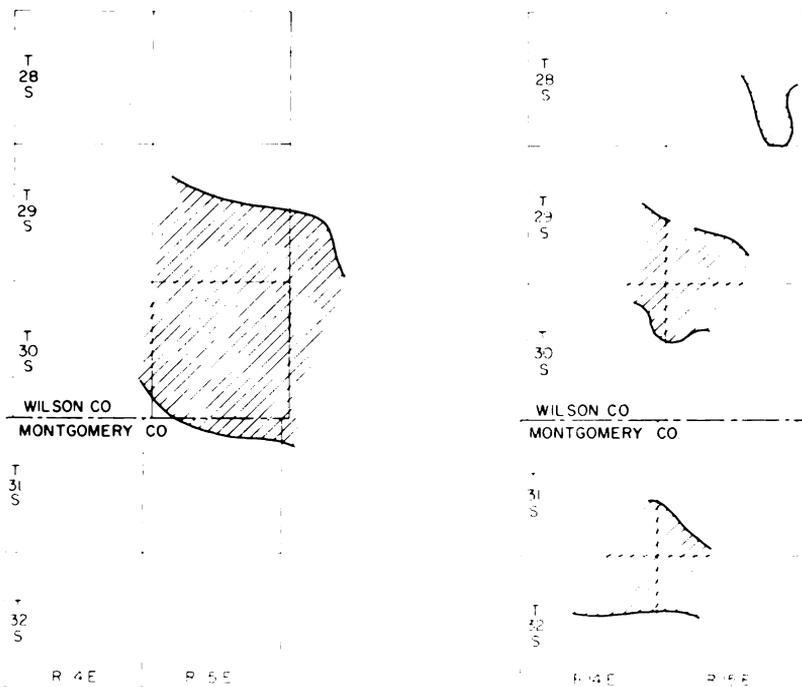
A. Spring Hill Limestone member greater than 30 feet thick.

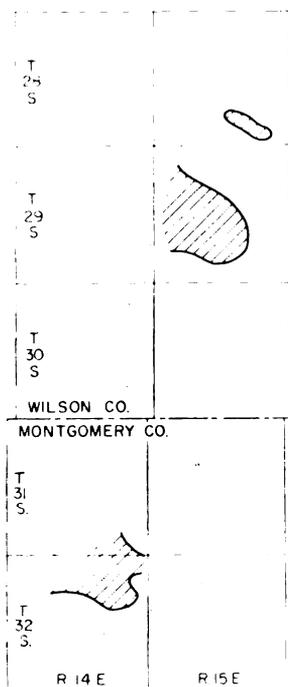B. Captain Creek **Limestone member** greater than **20 feet thick.**

Fig. 18. Maps showing, by pattern, localities where **Lansing limestone**

SUMMARY

1. Six more or less arbitrarily defined types of limestone make up the Lansing limestones in the Wilson-Montgomery County area. These have been termed algal-crust limestone, breccia limestone, fragment-pellet limestone, calcarenite, oölite, and carbonate siltstone.

2. Two principal fabric types have been recognized in Lansing limestones. One is the fabric of calcite mosaics that have been precipitated in open space. The other fabric is that of calcite mosaics formed through recrystallization of carbonate silt or fine skeletal debris by grain growth. Each of the fabric types displays distinguishing characteristics similar to those reported by other authors.

3. Algal crusts, skeletal debris, and carbonate silt accumulated

C. Stoner Limestone member greater than 15 feet thick.
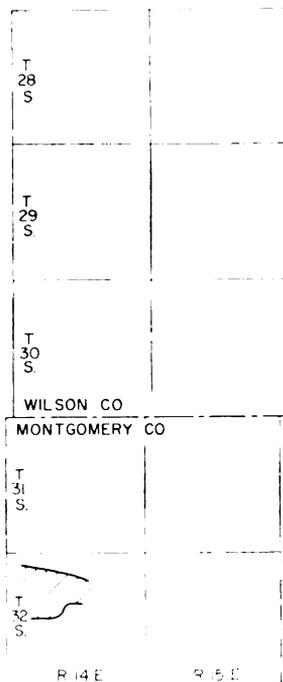
D. South Bend Limestone member greater than 15 feet thick.

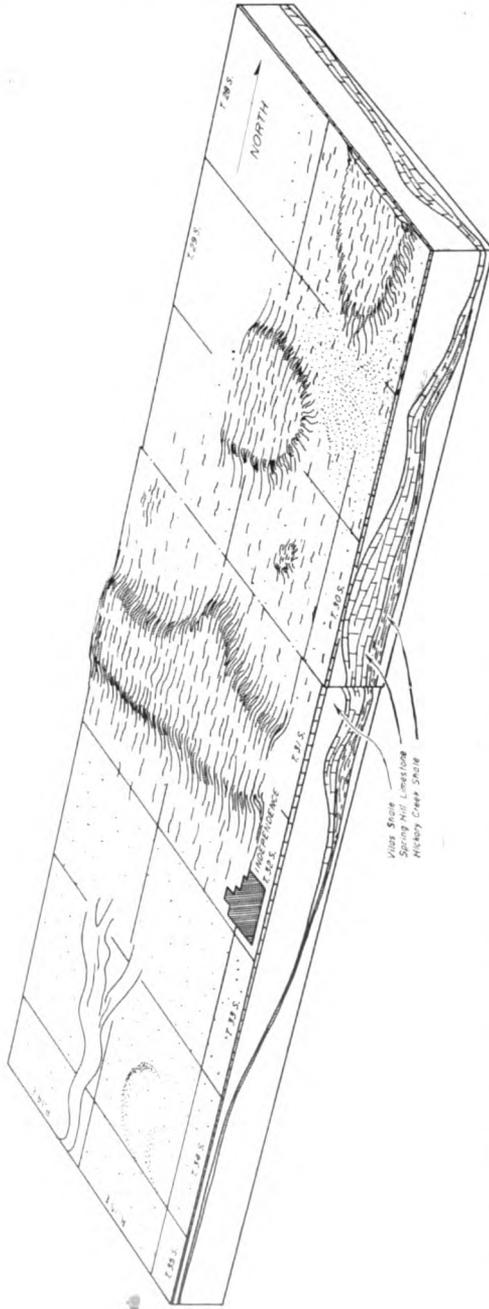members are abnormally thick (Merriam Limestone member excluded).

FIG. 19. Hypothetical interpretation of geographic relations during deposition of Captain Creek or Stoner Limestone members. Marine banks shown as elevated areas. Localities in which predominantly calcarenites and oölites accumulated are stippled. North is toward right, south toward left of diagram. Meandering, braided scour channel is shown in southern part of area on assumption that streams flowed across broad shoal area, transporting terrestrially derived clastic material from a distant southerly source.

in thickened calcareous lenses, which formed banks rising above the general level of the surrounding sea floor. The banks probably should not be regarded as wave-resistant reefs, because there is little evidence of frame-building organisms that would have been necessary to withstand vigorous wave attack. The banks were probably poorly consolidated when first formed.

4. Algal crusts have created voids for open-space precipitation, by serving as miniature umbrellas. The algal crusts caught carbonate silt and skeletal debris on their upper surface while they provided sheltered open spaces beneath. These open spaces were later filled with precipitated calcium carbonate.

5. The upper surfaces of banks probably rose into very shallow water and may have been exposed to the atmosphere from time to time. Breccia limestones may have formed on intermittently wetted mud flats, and development of open-space precipitate mosaics beneath algal crusts may have taken place only slightly below sea level.

6. Localization of solution pores in outcropping Lansing limestones has been influenced by a variety of lithologic features. Pores tend to be localized (a) along fractures, (b) within coarsely crystalline open-space precipitate mosaics formed beneath algal crusts and between breccia fragments, (c) at the contact of crystalline mosaics with carbonate silt or skeletal material, (d) within algal crusts, (e) at the contacts of skeletal particles, and (f) within dolomitized patches. It is possible that pore development in buried Lansing limestones that serve as oil-reservoir rocks is similarly controlled.

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