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NIAGARAN REEFS IN ILLINOIS AND THEIR RELATION TO OIL ACCUMULATION

BY

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NIAGARAN REEFS IN ILLINOIS AND THEIR RELATION TO OIL ACCUMULATION

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H. A. LOWENSTAM

INTRODUCTION

UNTIL THE STUDY of well cores late in 1943 revealed that the newly discovered Marine pool in Madison County was producing oil from rocks of Silurian age, there appeared to be little promise of oil in commercial quantities in the Silurian strata of Illinois. Detailed studies of the Marine pool[1] showed that the oil occurs in a Niagaran reef atoll, a type of oil reservoir not previously known in Illinois. Thus the Marine pool is an example of the stratigraphic-trap type of oil reservoir, in which the trap is formed by enclosure of a porous permeable reef lens in essentially impermeable interreef deposits.

After the nature of the reservoir in the Marine pool became known, exploration for similar Silurian reefs was a logical consequence. Several factors pointed to the existence of other buried reefs in Illinois, despite the fact that the Marine reef was separated by approximately 225 miles from the outcropping reefs in northeastern and northwestern Illinois. Observations on reef distribution in Silurian outcrops from Iowa to Ontario had long established the fact that Silurian reefs are not isolated but occur in groups. Also, the fact that the Marine reef was found to be as large as (if not larger than) any of the reefs in outcrops to the north indicated that environmental conditions favorable to reef development in Silurian time had existed as far south as the off-shore waters of the Silurian Ozark Island. On the basis of these observations, it appeared reasonable to assume that the reef at Marine was possibly linked through other reefs, then unknown, to the reef archipelago in the outcropping areas to the north,[2] a view subsequently strengthened through locating two other subsurface reef sites—not productive—northeast of the Marine reef.[3]

The present study is a systematic examination of the subsurface Silurian strata of Illinois to determine the occurrence and spacing of reefs, and to delineate their distribution as a guide for further oil exploration. An area bounded on the northwest by the Illinois River, on the west by a line 10 to 20 miles east of the Mississippi River, on the south by a line extending across the state from Kaskaskia Island, Randolph County, northeastward to Lawrence County, on the east by the Indiana border, and on the north by a line through Kankakee has been examined in detail. Within this area, practically all available sample sets and all electric logs of borings penetrating the entire Silurian system have been carefully examined, and records of wells that stopped in the Silurian, or even in the Devonian system, have been used in critical localities.

As the Silurian system elsewhere in Illinois appears to offer little possibility for oil production, it has been examined only in sufficient detail to outline regional sedimentational relations. Along the western border of the State, Silurian strata have been entirely stripped or greatly reduced in

[1] Lowenstam, H. A., and DuBois, E. P., Marine pool, Madison County—a new type of oil reservoir in Illinois: Illinois Geol. Survey, Rept. Inv. 114, 1946.
Lowenstam, H. A., Marine Pool, Madison County, Illinois, Silurian-reef producer: *in* Structure of Typical American Oil Fields, vol. III, Am. Assoc. Petrol. Geol. pp. 153-188, 1948; reprinted as Illinois Geol. Survey, Rept. Inv. 131, 1948.

[2] Lowenstam, H. A., and DuBois, E. P., op. cit., p. 30.
[3] Lowenstam, H. A., op. cit., p. 179, fig. 13.

thickness by repeated post-Niagaran erosion. South of the intensively studied area the Silurian strata apparently do not contain reefs (figs. 1 and 2), and north of it reef reservoirs have been found to contain fresh water rather than brine, minimizing the chance for oil in commercial amounts. Reefs were found only in Niagaran (Middle Silurian) strata.

The search for buried Niagaran reefs relies essentially on an understanding of facies characteristics and facies relations. The basic tool for facies analysis is the study of the lithologic character of well cuttings, of their fossil constituents, and of their acid-insoluble residues. Electric log, gamma ray log, and structure studies, although useful tools, are usually of secondary importance. Criteria for differentiation of reef, interreef, and reef-free deposits have been developed by a study of reef-bearing Silurian outcrops of northeastern Iowa, northern Illinois, northern Indiana, Wisconsin, Michigan, and Ontario, and of the reef-free outcrops of Oklahoma, Arkansas, Missouri, southern Illinois, Tennessee, Kentucky, and southern Indiana.

The reefs are organic structures, and their distribution in both time and space is most clearly defined in terms of their fossil content. Although this paper is written in terms of lithology, patterned to serve in exploration for oil, it could not have been completed without basic studies of the ecology of the Niagaran faunas.[4] Because the physical factors, both in present and past times, are expressed equally in the sediments deposited and in the character of the faunas and floras whose remains are enclosed in the sediments, studies of sediments and of organisms must be combined in order to achieve a satisfactory understanding of the environments which controlled both.

The fundamental aspects underlying the results presented here are to be published separately in a paper that will deal with the environmental setting, both paleonto-

[4] Lowenstam, H. A., Biostratigraphic studies of the Niagaran interreef formations in northeastern Illinois: Illinois State Mus. Sci. Papers, vol. 4, 1948.

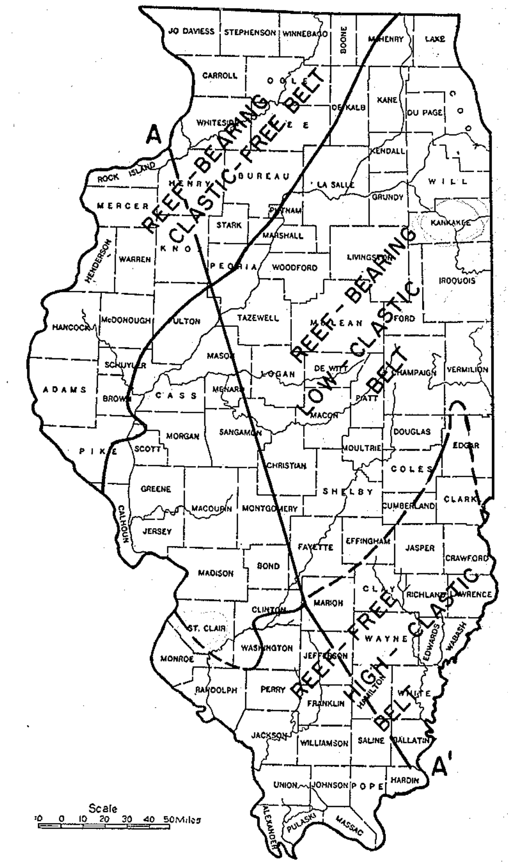


FIG. 1.—Niagaran sedimentation belts in Illinois showing line of cross-section (fig. 2).

logical and physical, which produced the reefs.

ACKNOWLEDGMENTS

The writer wishes to express his thanks to the following staff members of the Illinois Geological Survey: A. H. Bell, R. E. Grim, D. H. Swann, H. B. Willman, and L. E. Workman. Through discussions they materially aided in clarifying many of the problems which arose during the present study. The writer is indebted in particular to D. H. Swann whose criticism of the paper from the point of view of oil exploration brought out more clearly the criteria which will aid in locating subsurface reefs. D. B. Saxby assisted in the preparation of the maps.

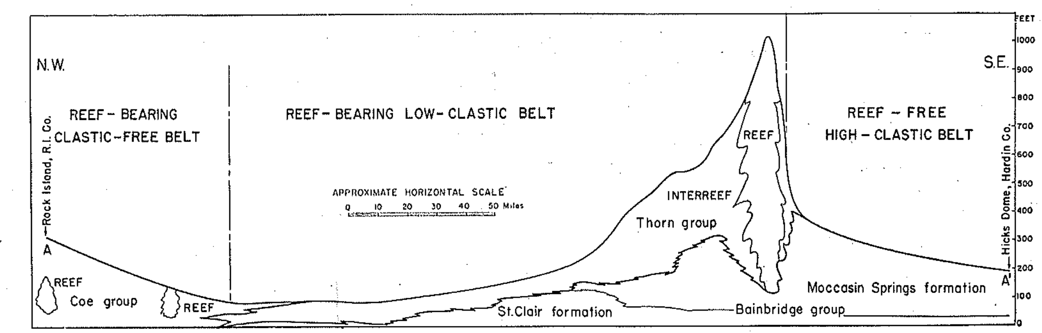


FIG. 2.—Diagrammatic cross-section of Niagaran strata from northwestern to southeastern Illinois along line indicated in figure 1.

NIAGARAN STRATIGRAPHY

Distribution.—Strata of Niagaran or Middle Silurian age are continuous over the greater part of the State. They have been removed by erosion only in north-central, west-central, and southwestern Illinois.

Thickness.—As there is no Upper Silurian in Illinois and the Lower Silurian (Alexandrian) is relatively thin, the isopach maps of the entire Silurian (fig. 3) and the Niagaran only (fig. 4) are very similar. Niagaran strata are thickest in a north-east-southwest belt 30 to 50 miles wide extending from easternmost St. Clair County through southeastern Kankakee County. Within this belt the thickness of the Niagaran strata is consistently 500 feet or more, and locally it increases to as much as 1,000 feet where reefs are present. The strata thin abruptly northwest and southeast of this belt to about 300 feet, except along the west foot of the LaSalle flexure between Woodford and Bureau counties where the thickness locally increases to nearly 500 feet. The causes of thinning in either direction from the belt of maximum thickness are unrelated, as the thinning to the southeast is depositional whereas that to the northwest is primarily due to erosion.

Sedimentation belts.—The most conspicuous regional variation in Niagaran lithology is the progressive decrease of terrigenous clastic content from southern to northwestern Illinois. Although the decrease in clastic content and concurrent changes in the carbonate rocks toward the northwest are continuous, the change is more rapid in two zones, and the rocks can best be visualized by describing them in three belts separated by the bounding zones. The bounding zones are actually narrow transitional zones with a steep clastic-content gradient, rather than the abrupt lines indicated on the map (fig. 1) and diagrammatic cross-section (fig. 2). In addition, a regional eastward decrease in clastic content from the Ozarks to the Cincinnati arch is evident but of relatively little importance within Illinois, becoming conspicuous only farther east in Indiana.

The southernmost belt can best be called the high-clastic belt, as it is characterized by limestones whose clastic noncarbonate content averages 35 to 40 percent. The sediments are all of the type seen in outcrops of the Bainbridge limestone in southeastern Missouri and southwestern Illinois.

Bordering it to the northwest lies a second northeast-southwest trending belt, the low-clastic belt, that is characterized by dolomitic limestone and dolomite averaging 15 to 20 percent clastic content. Rocks of the Bainbridge type are present in the lower part of the section in the entire belt, but are overlapped by, and grade laterally into, rocks of the kind seen in outcrops in the Chicago area and in the upper Wabash Valley.

The Niagaran rocks in the third belt in the northwestern part of the State are dolomite which commonly contains less than 5 percent insoluble clastic material, such as that seen in outcrops near Savanna, Illinois, in eastern Iowa, and in north-cen-

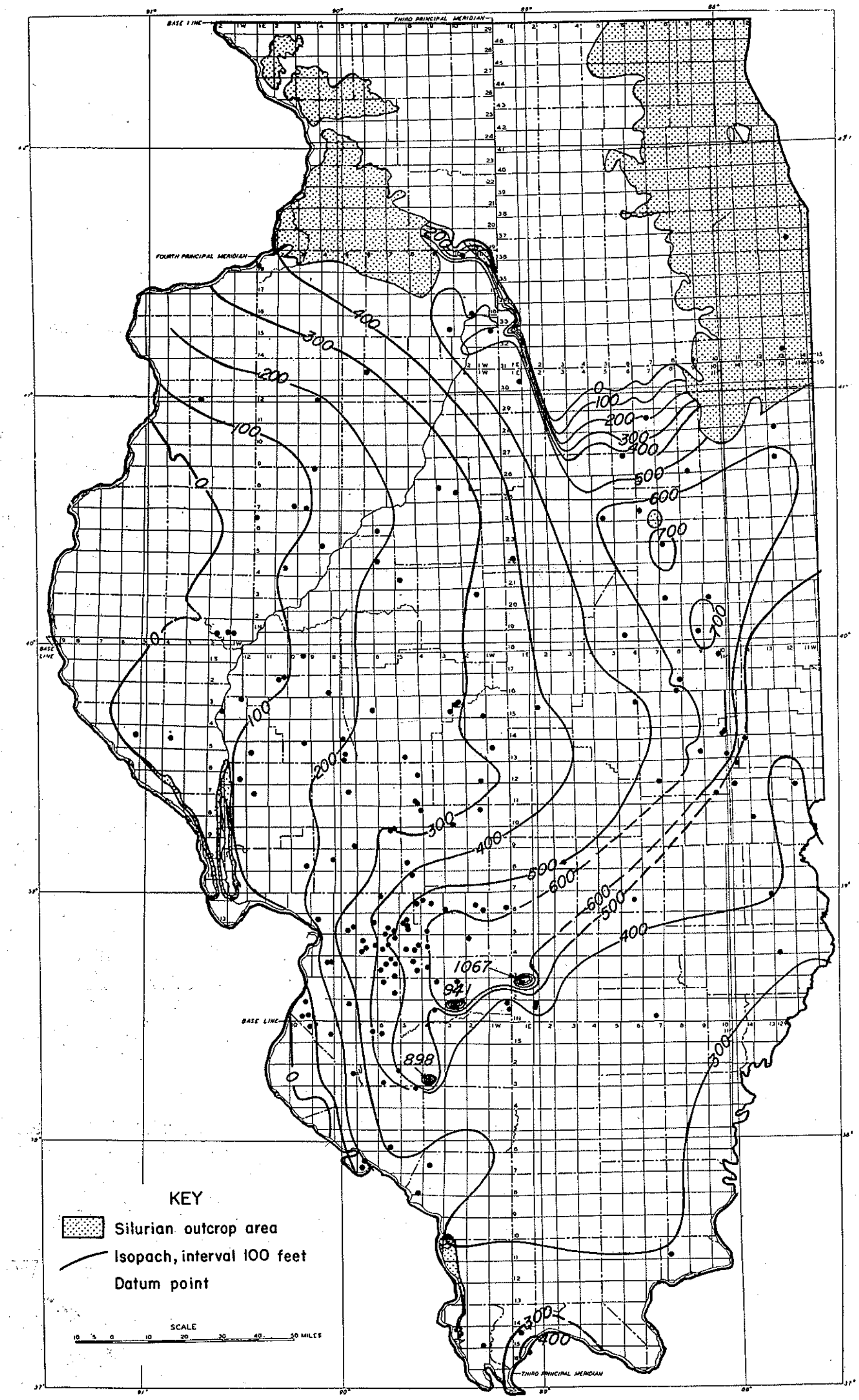


FIG. 3.—Thickness of Silurian strata in Illinois.

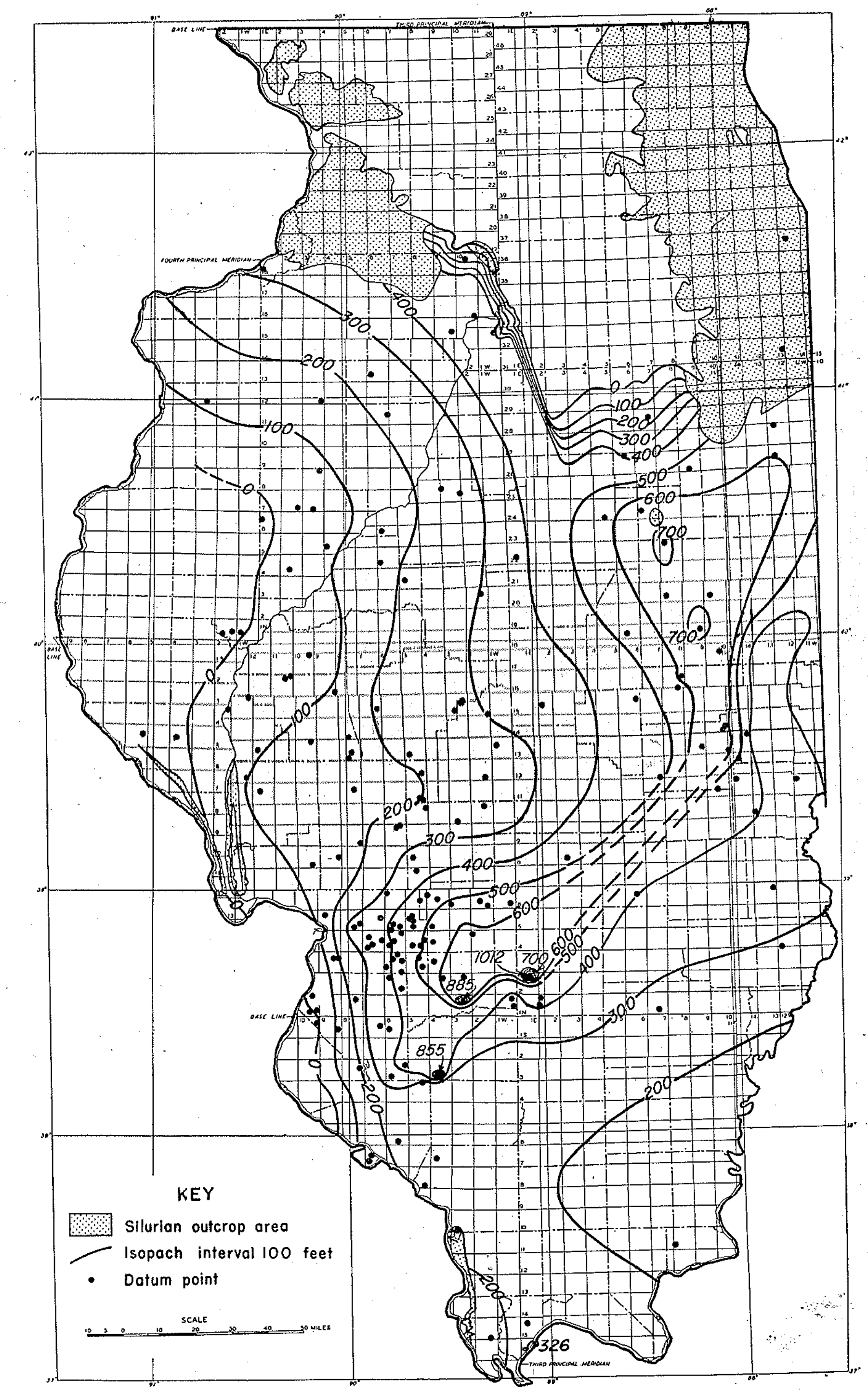


FIG. 4.—Thickness of Niagaran strata in Illinois.

tral Wisconsin, and in Michigan. This belt is called the clastic-free belt.

The two outer belts are relatively simple in that each contains only a few lithologic types. The middle belt is complex, containing wedges and even isolated lenses of the sediments characteristic of both of the other belts, in addition to lithologic types not represented in the other belts.

The two northern belts contain the remnants of a scattered archipelago of organic reefs and form the southwestern part of a large oval-shaped reef-bearing area which extended in the Niagaran sea for several hundred miles northeastward from the Ozark Island (fig. 7). The southern front of the reefs coincides with the border between the southern and central belts.

Outcrops in each of the sedimentation belts aid in clarifying the facies relations observed in well samples. The differences of the Niagaran deposits in the various outcrop areas are directly correlated to their position in the sedimentary belts outlined. The northwestern Illinois outcrops are located well within the northern belt of essentially pure carbonate rocks, those of northeastern Illinois within the northern portion of the central low-clastic belt. The erosional remnants of lower Niagaran deposits in west-central Illinois near Hamburg and in the Grafton area have the same relative position within the low-clastic belt as those of northeastern Illinois. Because these remnants are largely eroded to levels beneath the main reef-bearing horizons, it is uncertain whether the entire outcrop area or only part of it is within the reef border. The Niagaran exposures of southwestern Illinois and adjacent southeastern Missouri are located well within the southern belt of high-clastic deposits.

Differentiation into Groups

The composition of the rocks in the widely separated outcrop areas differs significantly and evidently reflects major differences in the sedimentary conditions that produced the varied belts. Minor environmental fluctuations occurred in each area, resulting in lithologic variations, which are the basis for the division into formations. The formations in each area, therefore, comprise a distinctive sequence which for convenience is considered to be a group (figs. 1 and 2). Because of the complex interfingering of the groups, especially in their contact areas, lateral and vertical variations in lithology are locally pronounced, and in well samples it is not generally possible to trace some of the individual formations far from the outcrop areas. Although the groups are contemporaneous and each group contains all of the Niagaran strata present in each outcrop area, it is only by recognizing them as separate units that the regional relations can be adequately discussed.

Bainbridge Group

The term Bainbridge, originally applied by Ulrich[5] to the entire Silurian sequence above the Cape Girardeau limestone in southeastern Missouri, was later redefined to include only the Niagaran strata. The Bainbridge strata have long been considered a formation but are herein redefined as a group.

The Bainbridge group consists of the Niagaran strata of the belt east and south of the Ozarks, an area which was apparently strongly affected by the Ozark Island during deposition. The group is characterized by a simple succession of two lithologically well-differentiated formations. The lower formation, the St. Clair, is considerably thinner than the upper one and consists of comparatively pure, commonly pink crinoidal limestone. The upper formation, the Moccasin Springs, comprises a thicker sequence of dominantly reddish and purplish high-clastic limestone and calcareous siltstone, commonly with greenish mottling. These two formations extend considerably beyond the area under consideration, the lower formation occupying a crescentic belt south and east of the Ozarks from west-central Texas to the central part of the Michigan basin, and the upper formation covering a narrower and shorter belt from south-central Oklahoma to central Illinois. At their geographic limits both formations interfinger with other Niagaran formations.

[5] Ulrich, E. O., *in* Quarrying Industry of Missouri: Missouri Bur. Geol. and Mines, vol. 2, 2nd ser., p. 110, 1904. Revision of the Paleozoic system: Geol. Soc. Am. Bull., vol. 22, pl. 28, 1911.

As a group the Bainbridge is distinguished from groups in the sedimentation belts to the north by its red, pink, and purplish colors, the predominance of limestone, the absence of chert, and the comparative persistence of lithologic types over wide areas. The group is also characterized by a large amount of interbedded shale, particularly in the Ozark-bordering zone, the generally high percentage of insoluble residues, averaging 35 to 40 percent, and the relatively large amount of clay in the residues.

St. Clair Formation

The lower formation of the Bainbridge group, the pink crinoidal limestone, has been named the St. Clair limestone[6] in the Batesville district in Arkansas. The name is here applied regionally to the pink crinoidal limestone of early Niagaran age throughout its distribution in the midwestern states except where local names are applicable to separate tongues in the marginal areas, as the Lego and Laurel tongues in Tennessee and a tongue in the base of the Joliet formation in northeastern Illinois and southeastern Wisconsin.

Distribution.—The St. Clair formation occupies an arcuate belt about one hundred miles wide, lying on the east and south sides of the Ozark highland, and extending discontinuously from western Oklahoma and west-central Texas through Arkansas, western Tennessee, western Kentucky, Illinois, and western Indiana to the central part of the Michigan basin. It can be seen in outcrops in the Arbuckles and Criner Hills in south-central Oklahoma and Arkansas, in southeastern Missouri and southwestern Illinois, and in the Tennessee Valley of western Tennessee, with fingers or tongues reaching the outcrop areas of the Nashville dome in Tennessee, southeastern Indiana, northeastern Illinois, and southeastern Wisconsin.

[6] Penrose, R. A. F., The Batesville region of Arkansas: Arkansas Geol. Survey, Ann. Rept., vol. 1, pp. 102-174, 1891. Modified by Williams, H. S., The Paleozoic faunas of north Arkansas: Arkansas Geol. Survey, Ann. Rept., vol. 5, pp. 277-301, 1900.

Thickness.—In the high-clastic belt of southern Illinois (figs. 1 and 6) the St. Clair limestone thickens progressively to the east and northeast from 20 or 25 feet in the outcrop area along the Ozark border[7] to about 80 feet near the Illinois-Indiana boundary. It also thickens to the north against the boundary of the central low-clastic belt. This northward thickening is more pronounced within the low-clastic belt, and the formation reaches its maximum Illinois thicknesses near the middle of the belt, where it is 80 to 150 feet thick over a considerable area beneath and just beyond the wedge edge of the overlying Moccasin Springs formation (fig. 5). Just north of the edge of Moccasin Springs cover the St. Clair locally reaches thicknesses of 220 feet, as in Ford, Champaign, Douglas, and Coles counties, but the pattern of extreme thicknesses is very irregular. The northward thickening appears to be due in part to the general thickening of the entire Niagaran and in part to the northward diminution of the clastics in the lower part of the Moccasin Springs formation; consequently beds are included in the St. Clair whose southern equivalents are considered Moccasin Springs.

The St. Clair formation thins northwestward from its area of greatest development by interfingering and gradation of the upper beds into rocks typical of the Chicago area, with only the basal member maintaining its identity as far as the northwestern boundary of the central low-clastic belt. This thin basal St. Clair tongue can be seen in outcrops in the Mississippi bluffs of western Illinois near Hamburg and in the Chicago area where it is more argillaceous and is represented in dolomitized form by the basal Joliet strata—the Osgood of Dunn,[8] Zones A and B of Willman,[9] and the basal unit of Lowenstam.[10]

[7] Ball, J. R., Some Silurian correlations in Lower Mississippi drainage basin: Bull. Am. Assoc. Petrol. Geol., vol. 26, p. 6, 1942.

[8] Dunn, P. H., Silurian foraminifera of the Mississippi basin: Jour. Paleo., vol. 16, p. 318, 1942.

[9] Willman, H. B., High-purity dolomite in Illinois: Illinois Geol. Survey, Rept. Inv. 90, p. 26, 1943.

[10] Lowenstam, H. A., op. cit., Biostratigraphic studies, p. 19.

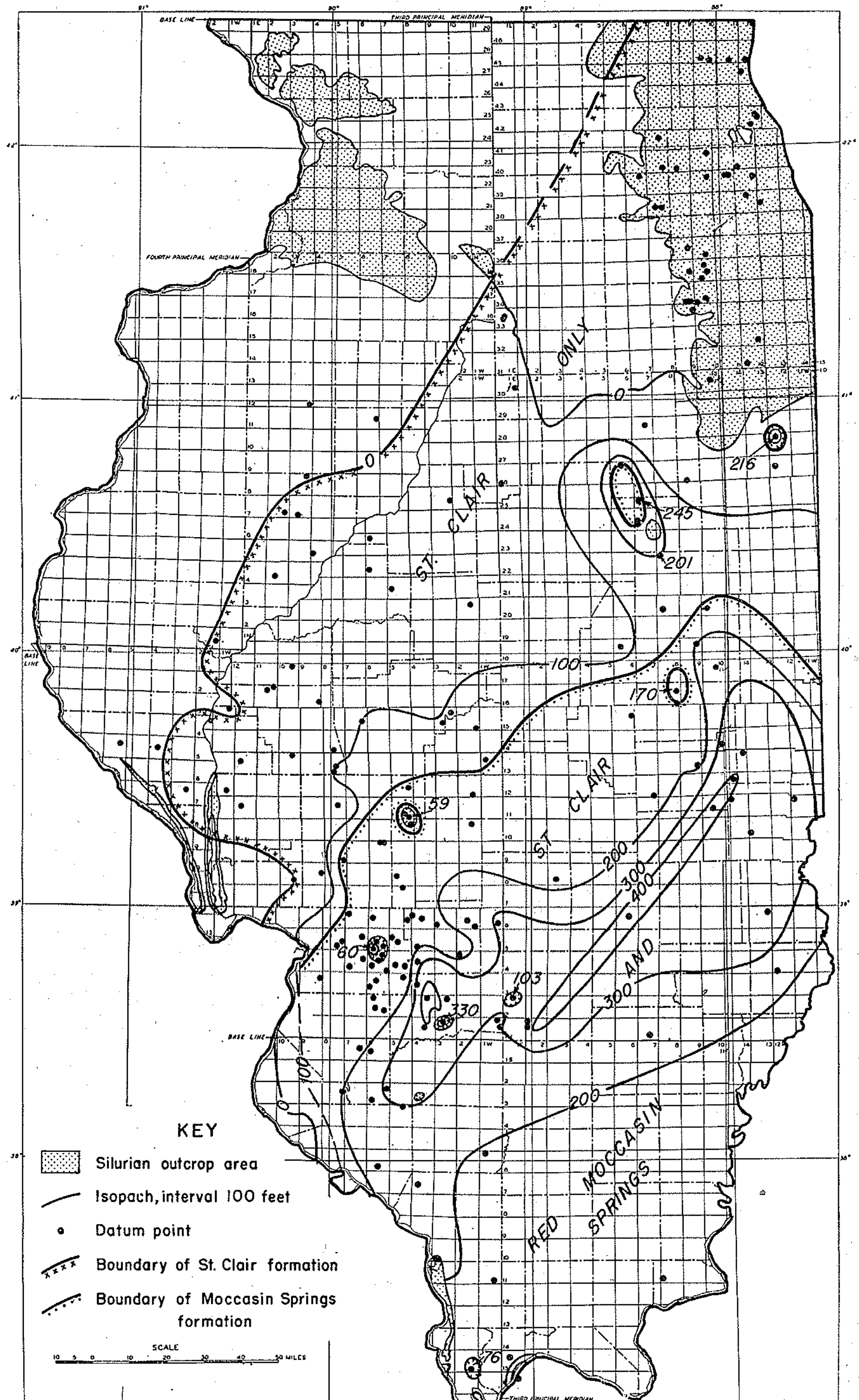


FIG. 5.—Thickness of predominantly red facies of Niagaran strata in Illinois.

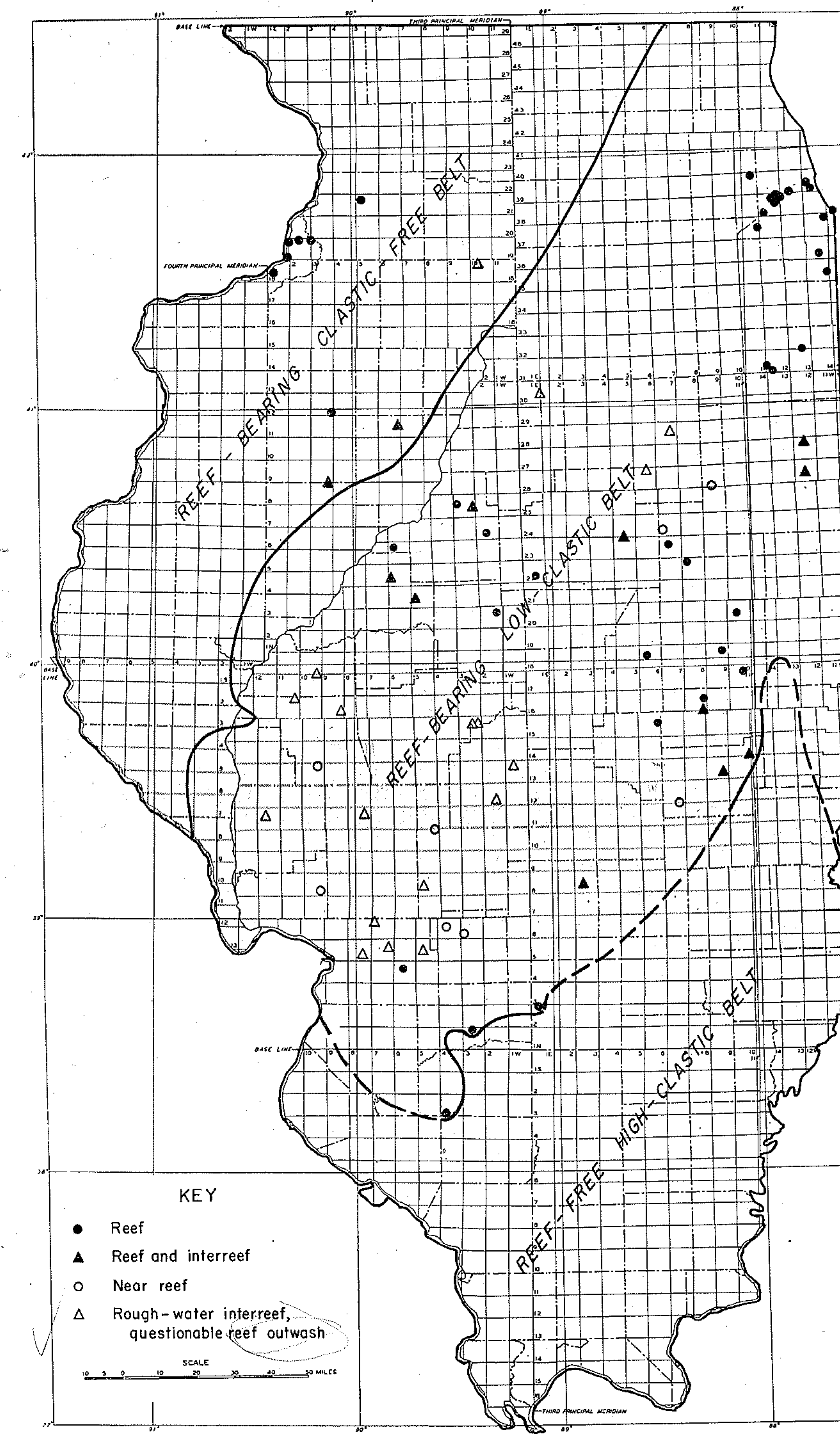


FIG. 6.—Niagaran reef occurrences and sedimentation belts in Illinois.

Lithology.—The St. Clair formation consists of buff to flesh-colored, occasionally white limestones that contain comparatively small amounts of terrigenous clastics and are prominently mottled with pink to red patches. Dissociated remains of small fragile crinoids are the main rock-forming constituents, particularly in the lower part of the formation. Ostracods form a conspicuous though less bulky element. Magnification shows that the characteristic pinkish to reddish mottling is caused largely by the color of the crinoidal remains and of part of the ostracod shells. The red ferruginous crinoidal remains are most prominent toward the base of the formation and decrease in density in the upper beds. In some localities they are partially recrystallized, appearing as irregular coarse calcite grains with only spots of the characteristic pink to red coloration.

The matrix of the basal crinoidal coquinas and the bulk of the upper beds consist largely of exceedingly fine-grained limestone that is light-colored, commonly buff, and slightly clastic. The terrigenous clastic content increases generally toward the top but averages about 10 percent. The clastics, predominantly silt, with less clay and exceptionally some very fine sand, are disseminated throughout the fine-grained limestone matrix, with some concentration in irregular patterns, laminae and thin layers, some of which are mottled red. A considerable proportion of the silt is concentrated in the abundant skeletons of arenaceous foraminifera which are very characteristic of the St. Clair limestone. Scattered grains of dolomite occur occasionally in the St. Clair strata. Chert is absent except for small quantities apparently introduced by groundwater in a narrow subsurface belt near the outcrop border in Monroe, St. Clair, and Madison counties.

The chief distinguishing features of the St. Clair formation as a whole are: the detrital character, the pink and red color of the fossil remains, the comparatively low clastic content, and the absence of chert.

Correlation.—Faunal studies still in progress indicate that the St. Clair formation in the southeastern Missouri and southwestern Illinois outcrop area is equivalent to the entire Osgood-Laurel-Waldron-Lego sequence of western Tennessee, rather than only its lower portion as suggested by Ball.[11] The uppermost St. Clair strata of southeastern Missouri are correlated with the Lego formation by A. R. Loeblich[12] of the United States National Museum on the basis of arenaceous foraminifera, and the writer's studies indicate that the basal beds of the Moccasin Springs formation, immediately above the St. Clair, are to be correlated with the Dixon formation which overlies the Lego.

MOCCASIN SPRINGS FORMATION

The upper formation of the Bainbridge group, here named the Moccasin Springs formation, includes all of the Niagaran strata that overlie the St. Clair formation in the outcrop area in Cape Girardeau and Ste. Genevieve counties, southeastern Missouri, and in Alexander and Union counties, southwestern Illinois. The most extensive exposure known, which shows all but the basal 5 to 15 feet of the Moccasin Springs formation, is located in a small box canyon in the Mississippi River bluff in the SE. 1/4 SE. 1/4 NW. 1/4 of sec. 24, T. 32 N., R. 14 E., Cape Girardeau County, Missouri (Jonesboro quadrangle), about three miles south of Moccasin Springs. It was described in detail by Ball.[13] The basal beds can be seen at Greither Hill, in the NW. 1/4 sec. 11 (interpolated), T. 36 N., R. 9 E., five miles southwest of St. Marys, and 2 1/4 miles southeast of Ozora, Ste. Genevieve County, Missouri, and in a road-cut in the SW. 1/4 SE. 1/4 SE. 1/4 sec. 11, T. 5 S., R. 3 W., two miles south of Thebes, Alexander County, Illinois.

Distribution.—The Moccasin Springs formation is less extensive than the St. Clair, occupying a discontinuous narrower semicircular belt that extends from south-central Oklahoma to central Illinois. The formation crops out in the Niagaran belts

[11] Ball, J. R., op. cit., Some Silurian correlations, p. 6.
[12] Loeblich, A. R., personal communication.
[13] Ball, J. R., Type section of the Bainbridge formation of southeastern Missouri: Bull. Am. Assoc. Petrol. Geol., vol. 23, pp. 595-601, 1939.

Sexton Creek limestone in the southern half of the State and its dolomitic equivalent, the Kankakee dolomite, in the northern half of the State.

The upper part of these Alexandrian formations is characterized by honey-yellow to light buff or brown microcrystalline limestone or fine granular dolomite which is quite pure but has scattered greenish argillaceous blotches. Glauconite pellets are common. Light-colored translucent chert containing sponge spicules is common, except in and near the northeastern Illinois outcrops.

Confusion of the Brassfield equivalents with basal Niagaran deposits is most likely in the southwestern portion of the State. Here the top beds of the Brassfield (Sexton Creek) may consist of maroon to weak pinkish crinoidal coquinas somewhat similiar lithologically to the overlying St. Clair formation.

The Brassfield can be readily differentiated in outcrop by the abundance of *Stricklandia pyriformis,* the characteristic zone fossil of the upper portion of the Sexton Creek and Kankakee formations. Although this fossil has been recognized in coarse well cuttings, the common occurrence of glauconitic pellets in the Brassfield equivalents (but not in the St. Clair) and of disseminated pyrite in the basal St. Clair (but not in the uppermost Brassfield) are of greater use in distinguishing the two.

A varied fauna of arenaceous foraminifera in the St. Clair serves as the most reliable identifying criterion. The foraminifera, particularly the coiled form, *Ammodiscus,* may be released through acidizing even in one or two cutting chips. Although a number of arenaceous foraminifera have been recorded from the Brassfield,[20] none have been found in the routine acidization of small samples of well cuttings, and *Ammodiscus,* which is very abundant in the Niagaran, has not been found in the lower beds.

[20] Dunn, P. H., op. cit., p. 319.

NIAGARAN SEDIMENTATION BELTS

Reef-free High-clastic Belt

Areal extent.—Reef-free Niagaran sediments extend across southern Illinois northward to a line that runs roughly from southern St. Clair County northeastward toward Vermilion County (figs. 1 and 6). At their northern border the relatively thin reef-free sediments abut against the thicker deposits which enclose the reef archipelago. Where the border can be traced in detail in two widely separate areas of limited extent, one in Washington, Clinton, and westernmost Marion counties and another along the Coles-Edgar county line, it appears sinuous rather than a straight line. Elsewhere this line of demarcation has been drawn on the basis of the facies relations of the few widely separated deep tests. The border of reef-free sediments also coincides with the northern limits of lower Devonian deposits.

Thickness.—The reef-free high clastic deposits are thinnest along the Ozark outcrop border in southeastern Missouri and southwestern Illinois. Represented here by the Bainbridge deposits, they are estimated to range in thickness between 150 and 180 feet, exact figures being unavailable owing to the lack of complete exposures. Thickening only slightly eastward beyond the outcrop border, the reef-free deposits remain essentially uniform in thickness, averaging around 225 feet over most of southern Illinois. Toward the north the deposits thicken, rapidly reaching their maximum thickness of about 450 feet in a narrow zone along the reef-archipelago front. A slight thickening at the southern tip of the State continues into western Kentucky and western Tennessee. The thinning in the St. Louis area is a result of post-Niagaran pre-Osage erosion.

Reef-bearing Belts

Reefs are the most obvious feature that distinguish the Niagaran rocks of the northern two-thirds of Illinois from those of the southern area. The reefs do not form a continuous barrier. They are isolated bodies surrounded by interreef deposits which form the bulk of the Niagaran rocks of the reef-bearing area.

The interreef sediments may be best described by dividing the reef-bearing area into two broad belts, one extending through central and northeastern Illinois characterized by impure limestones and dolomite with a moderate terrigenous clastic content, and the other occupying northwestern Illinois, where the interreef beds are relatively pure dolomites. The central Illinois belt is distinguished as the low-clastic reef-bearing belt, and the one in northwestern Illinois as the clastic-free reef-bearing belt.

The low-clastic belt in many respects is transitional between the reef-free high-clastic belt of southern Illinois and the clastic-free belt of northwestern Illinois. It contains representatives both of the impure red Bainbridge sediments which are characteristic of the reef-free belt and of the pure dolomites of the northwestern area. The environment of deposition of each of the outer belts was relatively stable; the southern area had still but muddy water, probably comparatively deep, during much of Niagaran time; the northwestern area had shallow, rough water, which carried little or no noncalcareous mud. The varying sediments of the inner low-clastic belt reflect rapidly shifting conditions of sedimentation.

The sediments of the reef-bearing belts are described in four sections. The interreef sediments of the low-clastic belt are described in detail in the first section and those of the clastic-free belt in the second. These interreef deposits are the normal, expected rocks within their respective areas. The reefs themselves are described in the third section. The last section is devoted to the effects of reefs on the immediate surrounding interreef sediments, for the discovery of more reefs will depend to a large extent upon the recognition of reef-modified interreef deposits and of the proximity of reefs as indicated by the modified sediments.

INTERREEF SEDIMENTS OF THE LOW-CLASTIC REEF-BEARING BELT

Areal extent.—The southeastern boundary of the low-clastic belt is marked by the sudden increase in thickness of Niagaran sediments which coincides with and is determined by the line of outermost reef bastions extending diagonally across the state from southwestern Washington County to Vermilion County. The belt extends beyond the State boundaries north and east to include much of Indiana, southeasternmost Wisconsin, and the southern part of the Michigan basin. The northwestern boundary of this depositional belt is marked by the last occurrences of appreciable amounts of noncarbonate or impure carbonate sediments and approximates the present course of the Illinois River (fig. 1).

Thickness.—Near the southeastern edge of this belt the Niagaran sediments have their greatest thickness within the State. The interreef deposits range from 450 to about 650 feet, and local increases up to about 1,000 feet are caused by the reef bodies. The gradual thinning along the western, northwestern, and northern borders of this thick belt is due to post-Niagaran erosion, but the thinning at the southeast margin of this belt is depositional in nature, and is correlated with the lack of reef-derived detritus in the thin highly compactible nonreef sediments of the southern belt. Here the thickness is reduced by as much as 150 to 250 feet within six to ten miles.

Facies.—The low-clastic reef-bearing belt as a whole displays the most complex sedimentation relations and the greatest variation in lithologic types and depositional environment of any of the areas under consideration. This is due, first, to its buffer position between the two extremes of quiet-water muddy sediments on the southeast and of rough-water nonmuddy sediments on the northwest and, second, to the superimposed effect of the reefs on the interreef deposits. Disregarding the pronounced local anomalies created by the reefs and confined to the immediate surroundings of the reefs, we can visualize the interreef sediments of this belt as consisting of two wedges. The lower wedge is thick at the southern edge of the area and thins to the northwest and northeast. It consists of extensions of the Bainbridge group northward from the southern reef-free area. The complementary upper wedge, thickest in the central and northern parts of the belt, consists of sediments of the Thorn group. Rapid lateral changes in the succession render the division of this wedge into separate formations of little value for the present discussion. The two wedges are largely or entirely contemporaneous. Bainbridge sedimentation, which covered nearly all the central low-clastic belt at the beginning of Niagaran time, was gradually restricted until by the end of the Niagaran it was confined to the southern belt, at which time the entire central belt was being covered by deposits of the Thorn type.

The facies analyses presented in the second Marine Pool report[21] refer to the relations in this low-clastic belt, "Facies A" being the Bainbridge wedge and "Facies B" the Thorn wedge.

Lower or Southern (Bainbridge) Wedge

St. Clair formation.—The St. Clair formation at the base of the Bainbridge wedge retains the lithologic character typical of the outcrop area northward to its area of maximum thickness at the north boundary of the reef-free belt. The upper portion of the sequence from this area on northward becomes progressively less crinoidal and consists predominantly of buff microcrystalline to very fine-grained limestone. The pink to red color of the remaining crinoidal elements is retained only in certain beds, and these too eventually change to beds with fewer crinoidal remains which are no longer pink. The basal portion maintains its formational identity over a larger area than the upper portion but tends to become more variable in that the typical pink or red crinoidal coquina with irregular silty or shaly partings occur only as lenticles in low-clastic lithographic limestone speckled with pink crinoids. This same type of change can be observed in the southwestern part of the St. Clair belt in the Arbuckle Mountains in Oklahoma. There the typical St. Clair pink coquina of the Marble City area can be traced westward to the correlative pink crinoidal member of the Chimney Hill formation which, in similar fashion, gradually loses its identity from east to west. As a result of dolomitization, the red to pink crinoidal remains lose their skeletal identity, and fuse into pink to reddish colored blebs (seen in dolomitic limestone in well samples), and eventually produce the pink to reddish mottling which can be seen in the basal Joliet dolomite and as occasional lenses in the upper Joliet dolomite of the Chicago area.

Moccasin Springs formation.—The dominantly red and purple high-clastic Moccasin Springs limestones and calcareous siltstones, which comprise the upper part of the Bainbridge wedge, thin toward the north and northwest and disappear near the middle of the belt. The basal brick-red high-clastic limestones and siltstones persist to near the limits of the formation. Only marginally does the clastic content decrease, accompanied by fading of the red colors into brown or changing to green.

Deposits in the upper part of the formation show more deviation from the typical rock types of the southern belt, the variations being greatest in the border zone against the overlapping facies wedge. The characteristic red and purple colors become more sparingly and irregularly distributed through this part of the section, occurring mostly in the form of faint mottling. Greenish-gray, olive-gray, and buff fine to microcrystalline limestone, which generally has a lower clastic content than usual, is interlaminated with greenish-gray to darker gray shaly calcareous siltstones.

Upper or Northern (Thorn) Wedge

The Thorn wedge thickens from a feather edge at the southern border of the low-clastic reef-bearing belt to at least 450 feet in the syncline immediately west of

[21] Lowenstam, H. A., op. cit., Marine Pool, pp. 167-174.

the LaSalle anticlinal belt. The original maximum cannot be determined because of the progressive thinning of the Niagaran deposits to the northwest as a result of erosion.

In contrast to the gradual regional changes within the underlying Brainbridge wedge, the lithologic succession in this wedge is marked by extreme variations that indicate rapidly shifting conditions of sedimentation. The changes in general are controlled by the reefs and vary in intensity with distance from the reefs. Only in the more extensive interreef areas, such as those surrounding the St. Jacob and Woburn South pools, is there a stable lithologic succession with a minimum of horizontal shift in facies.

In addition to the striking changes in vertical succession in this wedge, a wide lateral range from calcareous or dolomitic siltstone and shale to low-clastic limestone and dolomite is present, although pure clastic-free carbonate rocks are confined to the reefs. There are exceptions to any general statement concerning rocks as variable as these, but on the whole the interreef rocks of this wedge are characterized by an abundance of chert and silicified fossils, by prevailing gray to greenish color, lack of red and purple shades, and by moderate to low clastic content. Although extremely variable, the terrigenous clastics average perhaps 15 percent for the entire wedge. They consist predominantly of silt with smaller amounts of clay, mica, and very fine sand.

The majority of the lithologic components of this wedge may be found in any given stratigraphic position and in irregular distribution throughout the facies complex; and gradation from one lithologic type into another is a characteristic feature of the shifting facies. The lithologic types are genetically divisible into three major groups: rough-water deposits, still-water deposits, and intermediate types. The criteria for differentiating the different sediment groups are those previously determined from outcrop studies in northeastern Illinois.[22]

Rough-water deposits.—The rough-water deposits are very fine- to medium-grained light gray to buff limestone and dolomite which have the lowest clastic content of any interreef beds in the complex. The terrigenous clastic fraction consists of coarse silt and very fine sand. Micas and clays as a rule are absent. The rough-water deposits are fairly cherty and locally contain an abundance of poorly preserved silicified fossils. Glauconite is fairly common. Oolites can be observed locally where silicification preceded dolomitization, which suggests that they may have been more abundant before destructive dolomitization. The dolomitic phase is usually porous. The fossil density in the limestone is generally comparatively high. The fossils, predominately crinoidal remains, are of medium size, fairly robust, and locally form sorted coquinas.

Still-water deposits.—The still-water deposits range from dark-colored calcareous or dolomitic siltstone, which may be shaly locally, to very argillaceous limestone or dolomite.

The siltstone is dark brown, brownish-gray, dark gray or weak greenish-gray, in part very finely laminated, and conspicuously micaceous. It contains few fossils, which are always very small and of fragile build. Sporangites and less commonly graptolites and scolecodonts are characteristic fossil constituents. Chert is commonly absent. The siltstone occurs both in well-defined bodies and interbedded and interlaminated with other sediments. It is quantitatively subordinate in the southwestern portion of the wedge where it forms small lenticles. In the northeast it is more prominently developed and forms irregularly shaped bodies that appear to be continuous over wider areas. Examples of these different still-water siltstone types can be found in outcrops in the *Lecthaylus* shale and the *Astraeospongia meniscus* facies west of Blue Island,[23] in the lagoonal deposits at the base of the interreef strata exposed in Thornton quarry, in late Niagaran siltstone at Momence and west of Kankakee, and the Mississinewa shale facies in the Wabash Valley of northern Indiana.[24]

[22] Lowenstam, H. A., op. cit., Biostratigraphic studies.

[23] Roy, S. K., and Croneis, C., A Silurian worm and associated fauna: Geol. Ser. Field Mus. Nat. Hist., pp. 229-47, 1931.
Lowenstam, H. A., op. cit., Biostratigraphic studies, pp. 76-117.

The still-water limestone and dolomite deposits are olive-gray to medium gray and greenish-gray, dense, very fine-grained, commonly micaceous, and either very siliceous or very silty and shaly. Fine sand is occasionally present. They are commonly abundantly cherty and contain silicified fossils. Fossils are mostly crinoidal remains, are moderately abundant, and are uniformly of small fragile types. The chert encloses separate spicules and even complete skeletons of siliceous sponges. The olive-gray dense siliceous limestone and dolomite is confined to the southwestern part of the belt near the reef archipelago front, being replaced to the northwest and northeast by the silty gray to greenish-gray limestone and dolomite. The silty dolomite may be seen in northeastern Illinois in the interreef section in Elmhurst quarry and in the bluff exposures north of Lemont.[25]

Intermediate deposits.—The intermediate types cover the entire range between the high-clastic and very low-clastic carbonate rocks and make up the larger portion of the facies complex. In general these sediments are lighter in color than the high-clastic carbonate rocks, being light gray to light olive-gray, greenish-gray, and less commonly light brown and buff. The olive shades are confined to the southwestern portion of the wedge. Chert and silicified fossils are common. The clastic fraction commonly is concentrated in silty and shaly lenses and laminae, which may be irregular and wavy, producing nodular structures which can be recognized in coarse cuttings. The density and the physical character of the fossils in these intermediate sediments vary between the extremes of the end members.

Relations of the Two Wedges

Along the slanting boundary separating the two facies complexes of the low-clastic reef-bearing belt, intertonguing and gradation are found over a considerable area. As the boundary is approached there is a notable although irregular decrease of the clastic fraction of the Moccasin Springs formation, accompanied by fading and disappearance of the typical red to purple colors. The conspicuous increase in thickness of the underlying St. Clair formation in the area of disappearance of the Moccasin Springs formation may be the result of facies replacement of the former by the latter. Chert and glauconite, usually absent in the two Bainbridge formations, may occur in the transitional beds of the border area. In the overlapping Thorn strata the transition region is marked by the scattered occurrence of an occasional pink crinoid grain in the St. Clair position and of red and pink mottled shaly or silty limestone lenticles in the position of the Moccasin Springs formation.

INTERREEF SEDIMENTS OF THE CLASTIC-FREE REEF-BEARING BELT

The interreef sediments of the clastic-free belt are characterized by less complex sedimentation relations and by more limited variation in composition than interreef deposits in the low-clastic belt to the south. The distinguishing features of the sediments as a whole are the high carbonate content with little chert and a terrigenous clastic content estimated to average less than 5 percent, decreasing proportionately to the northwest across the belt. These practically pure carbonate deposits are uniformly dolomitized.

The predominant sediment is very slightly argillaceous dolomite which is porous, fine-grained, crystalline to granular, buff to white, and less commonly light gray and light brown. The clastic fraction consists of silt, very fine sand, and rarely of clay. Chert, glauconite, and silicified fossils may be present and are more prevalent in the southern portion of the sediment belt. The fossils are generally large and robust.

[24] Cumings, E. R., and Shrock, R. R., The geology of the Silurian rocks of northern Indiana: Indiana Dept. Conservation, Pub. 75, 1928.

[25] Lowenstam, H. A., op. cit., Biostratigrpahic studies, pp. 33-38, pp. 42-58.

Crinoidal remains and colonial corals form the common recognizable constituents in cuttings. Similar dolomite which is slightly more argillaceous, commonly greenish-gray or mottled and contains a few shaly laminae and lenses, is less common and occurs largely in the basal portion of the sequence. Oolitic dolomite, in which the oolites are obscure unless silicified, is less common.

Another rare type of interreef deposits consists of thinly laminated alternating light gray to buffish-gray exceedingly fine-grained dense granular to lithographic dolomite, evidently the dolomitized equivalent of the Solenhofen type of lagoonal lithographic limestone. These laminated dolomites carry a few exceedingly fragile fossils and appear to be the only still-water deposits represented in the area. They have been observed in outcrops only in the higher part of the sequence, as in the Anamosa deposits at Stone City, Iowa, and less extensively in pockets in the steeply dipping flank beds of the reef that is exposed in the quarry at Cordova, Illinois.

The rather limited variation in sedimentary types in this belt implies nearly continuous rough-water conditions, the variation expressing the degrees of water agitation.

REEFS

Distribution.—Reefs are developed in the two northern sedimentation belts, extending over the entire northern two-thirds of the State, but are discontinuous. There is evidence of small-scale, local reefs merging into atolls, as in the case of the Marine reef, and possibly in the Kankakee region, but there is no tendency of large-scale coalescence into barrier reefs, as in the Permian reefs of Texas and New Mexico. Instead the reefs comprise a loosely grouped widespread archipelago which extended regionally far beyond the borders of the State and formed a broad northeast-southwest trending eliptical belt around the central portion of the Michigan basin. As shown on the reef distribution map (fig. 7), the Illinois portion comprises the southwestern extremity of the archipelago which was anchored off the northeastern shore of the Niagaran Ozark Island. Erosion has obscured the border relations to the Ozark Island. The southern border of the reef archipelago, although imperfectly known, is distinguished by several frontal reefs as well as by differences in lithology which reflect the changes in sedimentation conditions from interreef to nonreef deposition. These reefs along the southern front are unusually large and tall; one is nearly 1,000 feet in height. They evidently represent the outer reef bastions which grew on the slope that connected the reef-bearing shelf to the north with the deeper reef-free bottoms to the south.

The reefs are exposed in great numbers in the outcropping areas of the archipelago, along the Niagaran escarpment all around the borders of the Michigan basin and in the western outlier in northwestern Illinois and adjacent Iowa, and have been described by several geologists. Publications by Hall,[26] Chamberlin,[27] and Graubau[28] trace the development of knowledge of these outcropping reefs. We owe much of our present knowledge on the reef structures to Cumings and Shrock[29] who systematically analyzed the reefs of the outcropping belt in general, with particular emphasis on northern Indiana, and to Shrock[30] who described the Wisconsin portion of the archipelago. Observations on the reefs of northeastern Illinois have been made by

[26] Hall, J., Physical geography and general geology: in Rept. Geol. Survey, State of Wisconsin, by Hall, J., and Whitney, J. D., 1862.

[27] Chamberlin, T. C., Geology of eastern Wisconsin: Geology of Wisconsin, vol. 2, 1877.

[28] Grabau, A. W., Paleozoic coral reefs: Geol. Soc. Am. Bull., vol. 14, 1903: Principles of stratigraphy: 2nd ed., A. G. Seiler, 1921.

[29] Cumings, E. R., and Shrock, R. R., op. cit., The geology of the Silurian rocks. Niagaran coral reefs of Indiana and adjacent states and their stratigraphic relations: Geol. Soc. Am. Bull., vol. 39, pp. 579-620, 1928.

[30] Shrock, R. R., Wisconsin Silurian bioherms (Organic reefs): Geol. Soc. Am. Bull., vol. 50, pp. 529-562, 1939.

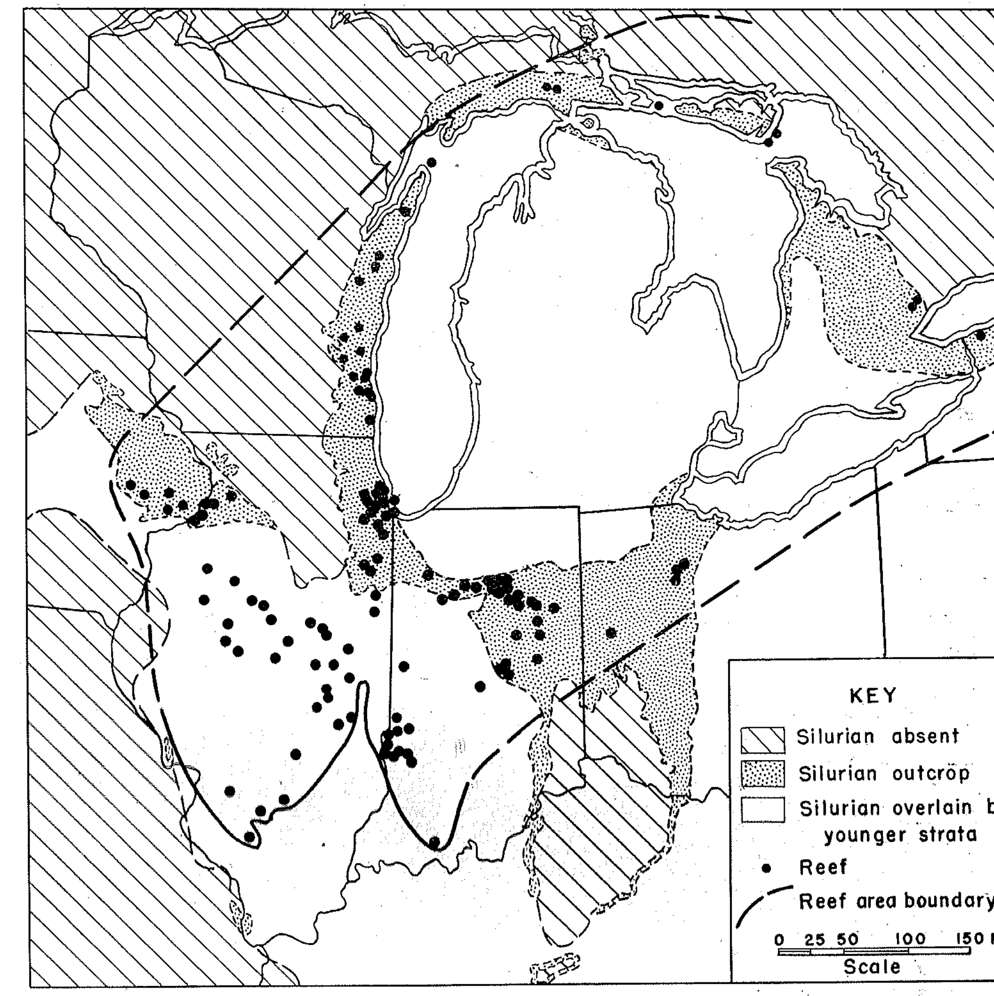


Fig. 7.—Distribution of Silurian strata and location of known reefs.

Cumings and Shrock,[31] Fenton,[32] Bretz,[33] and Lowenstam.[34]

Origin and classification.—The reefs are uniformly of organic origin. Erected by reef-building organisms, they were rigid structures which formed topographically raised shoals of various heights above the surrounding interreef bottoms. In their fossil state of preservation they form well differentiated bodies, which are structurally, lithologically, and faunally distinct from the horizontally bedded interreef deposits that enclose them.

The reef structures display little variation in the essential features of their building plans. They consist of one or two components. In the simplest form the reefs are represented only by the massive nonstratified reef proper, the reef core of Cumings and Shrock.[35] In other reef structures,

[31] Cumings, E. R., and Shrock, R. R., op. cit., Niagaran coral reefs.

[32] Fenton, C. L., Niagaran stromatoporoid reefs of the Chicago region: Am. Midland Nat., vol. 12, pp. 203-12, 1931.

[33] Bretz, J H., Geology of the Chicago region: Illinois Geol. Survey, Bull. 65, Pt. I, 1939.

[34] Lowenstam, H. A., op. cit., Biostratigraphic studies, pp. 31, 42-43, 131-133.

[35] Cumings, E. R., and Shrock, R. R., op. cit., The geology of the Silurian rocks, p. 140.

the core is flanked by reef-derived detritus, which is bedded and dips at various angles radially away from the core. The reef cores and flank beds are commonly sharply delineated. A distinct variation of the type with flank deposits is represented by the additional accumulation of reef detritus on top of the reef, as found in subsurface on the Marine reef in Madison County.[36]

Reefs with flank deposits are prevalent in the central low-clastic sedimentation belt, and reefs without flank deposits predominate in the northern clastic-free belt, although both types occur in both areas. Good outcrop examples of the reefs with flank deposits may be seen in the railroad-cut at the Big Four Station in Wabash, Indiana,[37] and in a partial section in the Thornton quarry south of Chicago. Several reefs without flank deposits are well exposed in the north-facing bluff east of Cordova in northwestern Illinois.

Shape of the reefs.—Information on the exact shape of the outcropping reefs is limited. The exposures commonly consist of single random vertical cuts which seldom either extend horizontally across the entire reef or expose both the top and base. Also many of the surface reefs have been deeply scalped by erosion. In rare instances, the gross features of the reef shape can be determined by a sufficient number of vertical exposures and by the topographic expression of many reefs as bedrock highs or klintar. The characteristic tendency of the reefs to stand up above the bedrock surface as klintar is due to the greater resistance of the reef rock to weathering and glacial scour as compared with the interreef rock. Such partially excavated reefs give outline patterns of the reefs in the horizontal plane.[38]

Information on the surface topography of the reefs in outcrops is lacking. Curiously enough, it is the surface topography which is the most accurately known feature of the Marine subsurface reef in Madison County.[39]

As far as has been ascertained to date, the reefs can be ellipsoidal, hemispheroidal, cuboidal, dome-, mound-, or ridge-like. Most forms may be found among both types of reefs, although there is a definite tendency toward ellipsoidal, hemispheroidal, and cuboidal shapes among the reefs without flank deposits and toward dome-, mound-, and ridge-shaped forms among the reefs with flank deposits. The core of the reefs with flank deposits is ridge- to dome-shaped. The subsurface Bartelso reef in Clinton County and the postulated Ayers reef appear to be ridge-shaped. The Sandoval reef is irregular diamond-shaped as far as can be ascertained from the compactional structure in the overlying Chester and Devonian strata.

The reefs are actually more complex in shape than indicated by their mapped outlines. The reefs with flank deposits commonly have serrated cores and flanks which reflect fluctuations in outward growth. The reefs without flank deposits generally have even borders. Fore-reef development comonly adds to the complexity of the reef forms. Fore-reefs developed on the flanks as well as in front of the main reef. Most of those developed on the reef flanks are small and many are drowned and overridden by the detrital flank beds. Prominently developed fore-reef ridges flank the outcropping Thornton reef and the subsurface Marine reef. At Marine the fore-reef ridge appears to be a composite of recurrent fore-reefs successively overwhelmed by flank deposits from the main reef. The fore-reef at the Thornton outcrop is likewise a complex structure; in the exposed section the flank deposits south of the main reef enclose several small fore-reefs, most of which are apparently limited by a larger bounding fore-reef ridge.

A composite reef form can be clearly traced only in the case of the Marine subsurface reef, whose topography and outlines indicate a horseshoe-shaped atoll.

[36] Lowenstam, H. A., and DuBois, E. P., op. cit., p. 19.
[37] Cumings, E. R., and Shrock, R. R., op. cit., Niagaran coral reefs, p. 588, fig. 7.
[38] Cumings, E. R., and Shrock, R. R., op. cit., The geology of Silurian rocks, p. 97, fig. 6.
Bretz, J H., op. cit., p. 66, fig. 51.
Shrock, R. R., op. cit., Wisconsin Silurian bioherms, fig. 4.

[39] Lowenstam, H. A., op. cit., Marine pool, fig. 11.

Size of the reefs.—The reefs are variable in size, ranging from a few feet to several miles in diameter and from a few feet to almost 1,000 feet in height. There is a definite relation between type and size of reef. The reefs without flanks are always small in area and particularly in height, being low-lying structures of prevalent horizontal growth, ranging from a few feet to a hundred feet or so in diameter. The reefs with flank deposits are larger and may show pronounced tendencies toward upward growth. They range from a few hundred feet to a known maximum of 3½ miles in diameter and from several tens of feet to almost 1,000 feet in height. The largest one known is the Marine subsurface reef, which covers approximately six square miles and is nearly 500 feet thick. The largest outcropping reef in Illinois is the Thornton reef south of Chicago, which is probably a little more than a mile in diameter.[40] The outer reef bastions along the southern edge of the reef archipelago are among the largest and are the highest reefs yet observed. These are the Bartelso reef in Clinton County, the McKinley reef in Washington County, and the Sandoval reef in Marion County, each of which has been entirely penetrated by a single boring. Each is estimated to have an area of a little more than a square mile, and is known to be between 800 and 1,000 feet thick.

Internal Reef Structure.—In outcrops reef cores are readily distinguishable from flank beds and interreef deposits by their massive appearance and lack of bedding. In some outcrops faint interrupted irregular growth lines may be seen in the solid reef mass, indicating temporary cessation of the normal continuous growth of the reef. The flanking detrital fans are commonly but not always sharply delimited at their contact with the reef core. They are invariably bedded. The bedding-planes characteristically are inclined radially away from the reef core and have dips ranging from a few degrees to 65 degrees.[41] Although commonly even-bedded, the beds are locally lenticular, particularly where they lens out by interfingering with the interreef deposits. In other places there is perfect gradation of the reef-flank beds into the horizontally bedded interreef deposits.

Reef-mantling detritus is definitely known only from the Marine subsurface reef. It is massive with a few indistinct bedding-planes that are horizontal in the upper part and inclined as much as 20 degrees in the lower part of the section.

The structural relations and bedding character of the reef components can be determined in subsurface only by means of coring.

Lithology.—Reef-flank and reef-core rocks are nearly identical, both in composition and small-scale texture, as would be expected because the flank rock is composed largely of fragments of the core constituents. They are differentiated primarily by their bedding and structural characteristics which are visible only in outcrops and well cores.

Although the reef-flank and reef-core rocks to a certain degree can be distinguished in the Marine reef,[42] this is in large part due to differential dolomitization, and the distinctions are not generally applicable. In other reefs both components may be entirely limestone or dolomite. Almost all the reefs are entirely dolomite except in the southwestern part of the archipelago in Madison, Clinton, Washington, and Marion counties where limestone and dolomitic limestone are conspicuous and are probably the prevalent rocks.

The reef-rocks as a whole are characterized by high carbonate purity, that is, by their small content of insoluble residue. They are, as a rule, 98 percent or more carbonates, the only common insoluble material being secondary pyrite. Their low insoluble content is in conspicuous contrast with the 15 to 20 percent found in the surrounding interreef deposits in the low-clastic reef-bearing belt, and particularly at the southern reef archipelago border where the bordering nonreef deposits average 40 percent insoluble. However, this

[40] Bretz, J H., op. cit., p. 61.
[41] Cumings, E. R., and Shrock, R. R., op. cit., Geology of the Silurian rocks, p. 142.

[42] Lowenstam, H. A., op. cit., Marine pool, pp. 174-76.

criterion of distinction between reef and interreef rock loses its value in the northern nonclastic reef-bearing belt, where the interreef deposits average 5 percent insoluble residue and quite commonly equal the reef-rock in purity.

Other regional lithologic characteristics of the reef-rocks are the large grain size and light colors of the limestone and the prevalent bluish-gray color and conspicuous vesicular texture of the dolomite. Chert is absent from the reef-rock. The absence of chert is an expression of environment, because the sponge population, whose skeletons supplied the silica for the chert of the interreef deposits, was confined to the still-water bottoms surrounding the reefs. Since still-water conditions were prevalent in the belt of low-clastic sedimentation but were the exception in the northern clastic-free belt, it is evident that chert as a criterion for reef and interreef distinction loses its value in the latter belt where chert is exceedingly rare. These criteria, previously outlined in the description of the Marine reef,[43] remain valid in the search for oil in other Niagaran reefs, because the critical area is located within the low-clastic reef-bearing belt, particularly along the border against the high-clastic reef-free sedimentation belt.

The lithologic characters of the reef deposits as compared to those of the normal Niagaran facies are distinguished in electric logs by consistently higher resistivity and particularly by consistently higher negative self-potentials in the low-clastic reef-bearing belt (pl. 1, wells 2, 3, 8, 10).

Fossil characteristics.—The reefs form the centers of maximum fossil density. This is to be expected because the core structure was erected as a loosely meshed frame by the skeletons of the reef-building organisms. The interstices of this frame were largely filled and the reef core was commonly flanked by the remains of the faunal associates of the reef builders, and by broken fragments of both. This is most noticeable in the reefs, largely limestone, in the southwestern part of the archipelago, where the detrital fans and caps of the reefs consist almost entirely of fossil debris. Syngenetic and diagenetic recrystallization and superimposed dolomitization have destroyed the identity of the fossils in large portions of the reefs, particularly in the cores, over most of the area of reef distribution. However, despite dolomitization, the outcropping reefs remain the sites of maximum fossil density in comparison with the surrounding interreef deposits. Casts and molds are the principal forms of fossil preservation in the dolomitized reefs.

The diversity of the invertebrate fauna also forms a striking feature of the reef assemblages, rarely approached and never equalled in the interreef assemblages. Colonial corals and stromatoporoids, apparently the main builders of the reefs, are most abundant in the reef cores, but crinoidal remains outnumber them conspicuously in the reef-flank beds. In physical appearance, the reef assemblages are characterized by the prevalence of large heavy-shelled robust forms which contrast sharply with the small fragile forms that characterize the still-water deposits. This criterion again is generally applicable within the low-clastic sedimentation belt but is not as useful in the clastic-free belt to the north, where the difference between the reef forms and those of the prevalent rough-water interreef is a matter of degree. The fossil remains on the reef-flank generally show random orientation except for colonial corals and stromatoporoids that grew in place and are parallel to the dip slope.

In well samples and in outcrops these criteria enable one to recognize reef assemblages. Numerical frequency, physical appearance such as large size and robust build, and assemblage characteristics such as relative abundance of colonial corals are determinable from well cuttings, but the dip-slope relations of colonial corals (an important clue in determining reef-flank deposits) are determinable only from well cores. The latter criterion could be utilized by means of oriented coring in wildcat borings that penetrate reef-flank deposits in order to discover the direction to the reef core.

[43] Lowenstam, H. A., and DuBois, E. P., op. cit., Marine pool, Madison County, p. 21.
Lowenstam, H. A., op. cit., Marine pool, pp. 174-176.

STRUCTURAL EXPRESSION OF REEFS

Studies at Marine have indicated that the Marine structure is largely controlled by the compaction of the interreef deposits around the relatively thick and rigid uncompactible reef body.[44] In general, the excess thickness of the Niagaran in the larger reefs produces dome-like structure in the beds that overlie the reef. This appears to be true of the Bartelso, Sandoval, and McKinley reefs in the oil-producing area, and of the Gibson City reef on the Champaign-Ford County boundary. The structural relief above the Gibson City reef is sufficient to allow removal of the Pennsylvanian strata by erosion, producing the Silurian inlier shown on the State geologic map. However, how much of this structural relief is due to the presence of the reef and how much of it is due to deformation has not been determined.

Compactional structures over reefs may in some places be differentiated from deformational structures by their patterns. As they are not related to the presumed lines of weakness in the crystalline basement which control most deformation structures, their position and the direction of their axes fall into the normal regional structural pattern only by coincidence. The shape of the individual structure is controlled by the reef mass and its topography. Narrow ridge-shaped reefs have rather narrow "anticlines" superimposed above them, but a horseshoe atoll such as Marine produces a crescentic structure. Any structure which appears "out-of-line" with regional trends or which appears unusual in outline should be examined with the possibility of reef rather than structural control in mind.

REEF BORDER

Evidence of the influence of reefs on their enclosing sediments is given by outcrop and subsurface data which are in large part complementary. Outcrops show contacts of small reefs to the best advantage, and show the minor details of the contact relations of large reefs. Because of the lack of suitable outcrops, most of our knowledge of the three-dimensional relations of large reefs to their surroundings and of the effect of these reefs on adjacent interreef sediments has come from subsurface information. The well records, although spaced too far apart to show the fine detail given by outcrops, are admirably suited for outlining the broader aspects of reef influence.

The lithologic contrast at the reef border is more pronounced in the low-clastic central belt than in the purer carbonate belt of northwestern Illinois, and the contribution of the reef to the surrounding sediments is best recognized in that part of the low-clastic belt where the interreef deposits consist of the Moccasin Springs formation. Shifts in the character, and particularly in the size distribution, of the clastic portions of the sediments form sensitive indices of the effects of reefs on their environment; the bright colors of the clay in the Moccasin Springs formation allow ready recognition and tracing of changes in the distribution of the clastics.

The contacts between small reefs of the flankless type and the surrounding interreef deposits are usually sharp. In the simplest examples the interreef deposits dip over and under the enclosed reef bodies with no obvious lithologic changes, as may be seen in an unnamed flagstone quarry half a mile north of Lemont, a short distance southwest of Chicago.[45]

The larger reefs with flank deposits commonly show more complex boundary relations, the interreef deposits interfingering with flank beds or occasionally grading imperceptibly into them. Interreef fingers may extend a considerable distance into the reef-flank. The first recognition of an extensive zone of influence surrounding a Niagaran reef was at Marine.[46] The present study has indicated that the Bartelso, McKinley, and Sandoval reefs, several reefs

[44] Lowenstam, H. A., op. cit., Marine pool, pp. 179-185.

[45] Lowenstam, H. A., op. cit., Biostratigraphic studies, p. 29.
[46] Lowenstam, H. A., op. cit., Marine pool, p. 176, fig. 10.

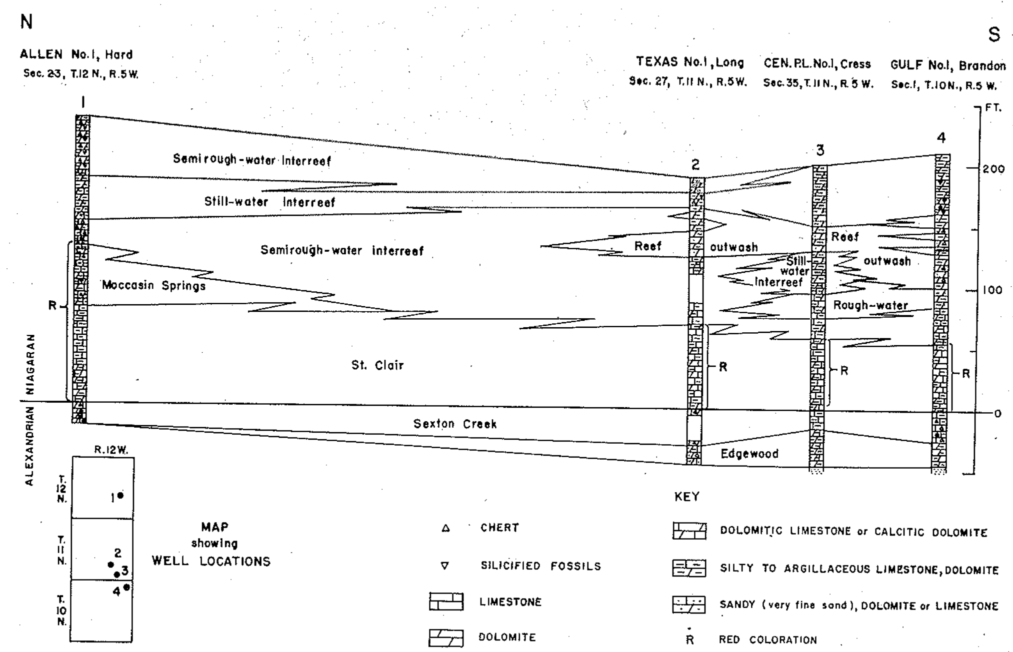


FIG. 8.—North-south cross-section of Silurian strata in northeastern Montgomery County showing reef proximity by reef outwash and by local thinning of Bainbridge (St. Clair and Moccasin Springs) strata in the opposite direction from the regional trend. The strata above the Bainbridge are the Thorn group.

in Douglas and Champaign counties, and a postulated reef in northeastern Montgomery County (figs. 5, 6, 8) have had a noticeable effect on the surrounding sediments.

Reef influence has been observed as far as two to eight miles beyond the reef edge. The distance is to a certain extent a function of reef size; larger reefs have larger zones of influence. It is also a function of direction. Winds and waves in Illinois during Niagaran deposition were apparently predominately from the south, as indicated by the configuration of the Marine reef and by distribution of reef outwash and of terrigenous clastics which were carried beyond Marine, Bartelso, and the other less well-known reef occurrences. At Marine, recognizable reef detritus extends no more than half a mile south of the reef but at least a mile north of it, and some effects can be noted nearly eight miles north.

A reef affects the surrounding sediments in two ways. First, the reef contributed to the surrounding sediments rather pure carbonate fragments in the form of well graded organic debris, ranging from sand size adjacent to the flanks to clay size at the limit of reef influence, possibly a number of miles distant. Second, the fine terrigenous clastics which would normally have settled in the reef area were transported past it because of the turbulence caused by shallow reef waters. The by-passing land-derived sediments were then deposited to the lee of the reef in amounts which appear abnormally large. These clastics are also graded, the silt portion settling closer to the reef than the clay portion.

As a result of the two processes described above, one can recognize two divisions in the zone of modified interreef sediments surrounding a reef. The inmost zone surrounds the reef but is most extensive on the northern lee side and is quite narrow on the windward southern side. This zone was characterized by considerable turbulence which is expressed by a maximum of reef-derived carbonate sand and by virtual absence of clay-size material, either reef-derived or terrigenous, except possibly flocculated clay. It can therefore be recognized by being somewhat thicker than the normal regional interreef section, by having purer carbonate rocks, and by having little or no clay or (in the case of Moccasin Springs sediments) red color. There may be fingers of fine-graded coquina, principally crinoidal, but containing recognizable fragments of stromatoporoids and colonial corals of which *Favosites* is most common. Recognizable fragments of corals and stromatoporoids are practically never seen in cuttings from normal interreef sediments in this belt.

Lapping around the lee edge of the inner zone is a semicircular zone that has unusually large amounts of clay-size material, both that derived from the reef and the terrigenous material carried past it. Wells in this zone show abnormally thick Moccasin Springs type sediments, as recognized by the trace red and bright green colors of the clay. Otherwise the sediments appear normal and it is unlikely that this zone of thickened clay deposition can be recognized when the interreef sediments are of types other than the Moccasin Springs. Intensive study of thin-sections or of heavy minerals in the insoluble residues of interreef carbonate rocks may develop criteria for recognition of this zone in other areas.

The simplest method of recognition of strata near large reefs in the southern portion of the low-clastics reef-bearing belt, where the Moccasin Springs is present and the possibilities of oil in the Niagaran are greatest, is the preparation of an isopach map of the red-colored part of the Moccasin Springs formation. Beneath a reef and the adjacent inner zone of reef influence where the water was turbulent, the red sediments are abnormally thin. They thicken radially, probably reaching the normal regional thickness abruptly to the south. To the north, northeast, and northwest, the area of abnormally thin red sediments is surrounded by a narrow semicircular fringe in which red sediments are abnormally thick. This thickening is the more noticeable because it lies in the direction in which the red sediments are regionally thinning.

The broad picture given above is probably oversimplified. It is known from outcrops that beds containing rather large amounts of terrigenous clastics may abut directly against a big reef and even creep up on the flanks, as at Thornton and Elmhurst in the Chicago region. Beds of pure dolomite, identical in texture and color to reef rock and representing the fine-grained fraction of reef detritus, are interbedded with high-clastic beds at Elmhurst and Thornton right up to the reef margin.[47] These occasional occurrences of high-clastic beds immediately adjacent to a reef probably are deposits in quiet-water pockets or semi-lagoons protected by reef arms.

Because of the prevalence of rough-water conditions which scattered the reef-detritus widely over the interreef tract, there is little lithologic contrast between reefs and their surrounding interreef deposits in the clastic-free belt of northwestern Illinois. This is best illustrated in the bluffs a short distance east of Cordova.

There is evidence that at least some of the Niagaran reefs settled into the nonreef substratum during their growth. The settling resulted in sagging of the interreef beds down toward the reef flank, as is shown at Elmhurst. That this sagging occurred during deposition of the sediments is indicated by black shale sediments which are confined to the sagged portion adjacent to the reef border and are indicative of stagnant conditions in localized depressions. The squeezing of the substratum out from under a reef has been described for a modern reef[48] and has been observed at a forereef at Thornton described earlier. Should this phenomenon occur in a subsurface reef it would be recognized by an extremely local bulging of Moccasin Springs type sediments right at the reef border.

NIAGARAN OIL POSSIBILITIES

In Illinois the Silurian rocks which show the greatest promise as oil reservoirs are the Niagaran reef lenses. Oil production from the Niagaran reefs of Illinois is of

[47] Lowenstam, H. A., op. cit., Biostratigraphic studies, pp. 46, 131-133.

[48] Cited in Cumings, E. R., and Shrock, R. R., The geology of the Silurian rocks, p. 145.

two distinct types. The reef rock itself may act as the reservoir, or overlying Mississippian and Devonian formations may produce oil from the structures formed as a result of differential compaction over the rigid reef bodies.

Oil has been produced from Devonian and Mississippian rocks above several known Niagaran reefs: Marine, Sandoval, Bartelso, and McKinley. It appears quite possible from a study of the structural relations as shown on upper horizons that certain other pools, such as Tonti and Patoka, may be underlain by Niagaran reefs.

The bulk of the oil produced at Marine has been directly from the Niagaran reef body. In addition, an undetermined proportion of the "Devonian" production at Bartelso has been from Niagaran reef rock, and some of the Sandoval production may have been from the underlying reef. Niagaran oil is being produced from the reef at McKinley pool, Washington County.

As the Niagaran reef production found to date has come from the large reefs near the reef front, and as there are considerable areas near the projected portion of the reef front in which the Niagaran is still untested, it appears that further major Niagaran oil production is most likely to be found in the southeasternmost part of the reef-bearing area (fig. 9). It should be pointed out that there is little control for the location of the reef front between western Marion County and Coles County. The actual front is presumably sinuous in this region, showing extensive embayments and prominent reef bastions as it does in the area to the southwest and northeast in which it can be mapped with greater accuracy.

It is theoretically possible that some reef outliers occur south of the archipelago border, as reef development might have started there during the relatively clear-water phase of St. Clair deposition.

The northeastern limit of the area of greatest likelihood of Niagaran reef production is the LaSalle anticlinal belt, as it appears that all commercial oil has been flushed from reefs on and beyond this structure. That commercial oil at one time was present in the Niagaran reefs of the LaSalle anticlinal belt and of the Chicago outcrop area is indicated by shows of residual "dead" oil through 200 feet of the Niagaran reef penetrated three miles north of Tuscola in Douglas County, by similar shows in Champaign and Ford counties wells, and by the well known asphalt occurrences in the outcropping reefs of the Chicago area.

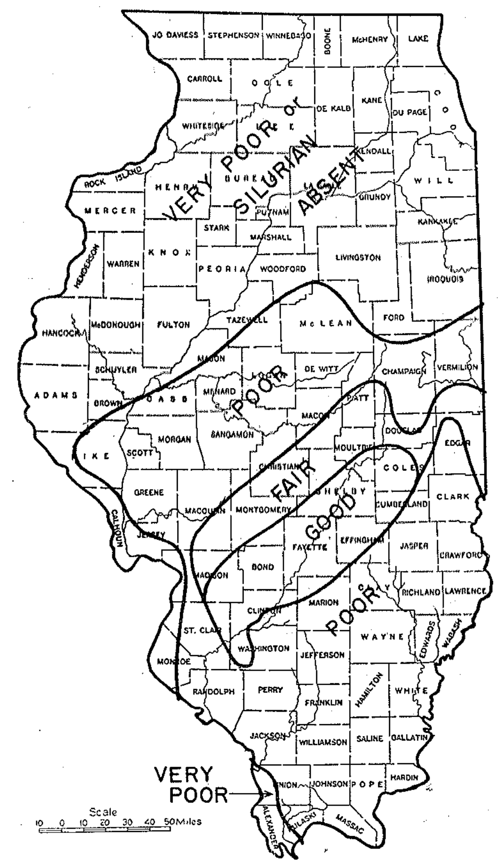


FIG. 9.—Silurian oil possibilities.

Northwest of the belt of greatest reef development and preservation is a parallel belt which presents fair possibilities for reef production (fig. 9). It seems likely that the reefs in this area were smaller than those closer to the front, and in addition they must have been truncated by pre-New Albany as well as pre-Middle Devonian erosion.

Deeply eroded reefs may be present and may produce oil in the central Illinois area with poor possibilities (fig. 9). In addition, it is largely within this area that porosity and permeability related to erosional surfaces may be expected in various nonreef Silurian rocks, with the possibility of light oil production.

The points of greatest significance in the search for further Niagaran reefs may be summarized as follows: The reef-rock proper always consists of practically pure carbonates, either limestone or dolomite, that have higher electrical resistivity than normal interreef rocks. Reef dolomites are invariably blue-gray in color, coarse-grained, and vesicular. Reef limestones are pink to white coquinas, formed almost exclusively of coarse unsorted fossil debris in which corals and stromatoporoids are important constituents. Chert is never present. The two reef rocks are replaced by varied impure carbonate rocks in the common interreef areas. The Niagaran rocks are abnormally thick at reef cores.

In the critical area for oil production where the Moccasin Springs formation is present, reef proximity may be most easily recognized by an abnormally thin section of Bainbridge red-colored beds closest to the reef and by abnormally thick red-colored sections at some distance to the lee of the reef. Fingers of well sorted fossil debris, chiefly crinoidal but containing noticeable amounts of coral constituents, extend some distance from the reef. Although certain interreef beds may approach these fingers in purity and in fossil density, the coral content is a reliable index for reef proximity. Relative purity of the Niagaran section in general strongly suggests nearness to a reef. All these criteria for reef proximity are applicable only within the southern two-thirds of the low-clastic reef-bearing belt indicated on figures 1 and 6, as they cannot be applied when the interreef sediments as a whole become relatively pure and the red Moccasin Springs formation becomes patchy toward its feather edge.

Structural highs occur in the beds that overlie reefs, due to the thicker reef section and to the compactibility of the interreef sediments. These structural highs imperfectly reflect the reef topography and outline, and therefore bear only coincidental relation to the normal regional pattern of deformational structures. In general, alignment of reef structures may be more or less parallel to the reef front. Known structures in higher beds which do not fall into the regional structural framework should be re-examined for possible reef influence. In some instances there may be superposition of reef-controlled structures on deformational structures.

As reefs would not influence the structure of underlying beds, seismographic reflections from the "Trenton" will not indicate the presence of Niagaran reefs, although seismographic records of horizons above the Niagaran should prove useful. Gravity anomalies have proved successful in locating Permian reefs in west Texas, but it is not known whether there is sufficient difference in the density of reef and interreef Niagaran sediments to produce recognizable anomalies. The physical property of reef-rock which appears to offer the greatest possibility for direct geophysical detection is its electrical resistivity, which averages several times greater than that of the typical interreef sediments.

Figure 6 indicates all known reefs in the area critical for oil production, although it is not complete for some areas in western Illinois. In addition it indicates a number of occurrences of reef flanks and reef-influenced interreef deposits in wells in the critical area. The most important of these near-reef occurrences can be summarized.

The Kingwood Oil Company 1 Gaffner well in the SW.1/4, SE.1/4, NE.1/4, sec. 30, T. 6 N., R. 3 W., Bond County, penetrated reef outwash containing fragments of reef-building corals and well assorted crinoidal coquina. It therefore appears likely that the nearby gas-bearing Ayers structure[49] is developed over a ridge-shaped Niagaran reef.

[49] Payne, J. N., Structure of Herrin (No. 6) coal bed in Madison County and western Bond, western Clinton, southern Macoupin, southwestern Montgomery, northern St. Clair, and northwestern Washington counties: Illinois State Geol. Survey, Circ. 71, 1941.

Three wells in northwestern Montgomery County (fig. 8), the Gulf 1 Brandon well, sec. 1, T. 10 N., R. 5 W., the Central Pipe Line 1 Gees well, sec. 35, T. 11 N., R. 5 W., and the Texas 1 Long well, sec. 27, T. 11 N., R. 5 W., are all within the inner zone of reef influence as indicated by the fact that the Moccasin Springs formation has been replaced by reef outwash and unusually pure low-clastic dolomite and dolomitic limestone. Of the three wells, the Gulf 1 Brandon well appears to be closest to the reef because it has a thin St. Clair section and contains the greatest amount of reef outwash. The presence of this postulated reef is strengthened by the occurrence of 50 feet of normal Moccasin Springs strata in the Alan 1 Ward well in sec. 23, T. 12 N., R. 5 W., 8 to 9 miles from the other wells and in the direction in which the Moccasin Springs formation is regionally disappearing. This last well is in the outer zone of influence in which clay-sized clastics and reef outwash are dumped in the lee of the reef.

The Continental Oil Company 1 Beachy well, sec. 13, T. 15 N., R. 6 E., Moultrie County, penetrated 160 feet of reef core and reef outwash and an additional 20 feet of reef-influenced sediments beneath the reef material. This would indicate that the reef began its growth not at the location of the Beachy well, but at some other point nearby. This reef is indicated on the regional reef distribution map of the second Marine pool report.[50]

The Carter 6 Brauer well, sec. 21, T. 8 N., R. 3 E., the deep test in the northern part of the Louden pool, penetrated interfingering reef outwash and core rock as well as intereef sediments.

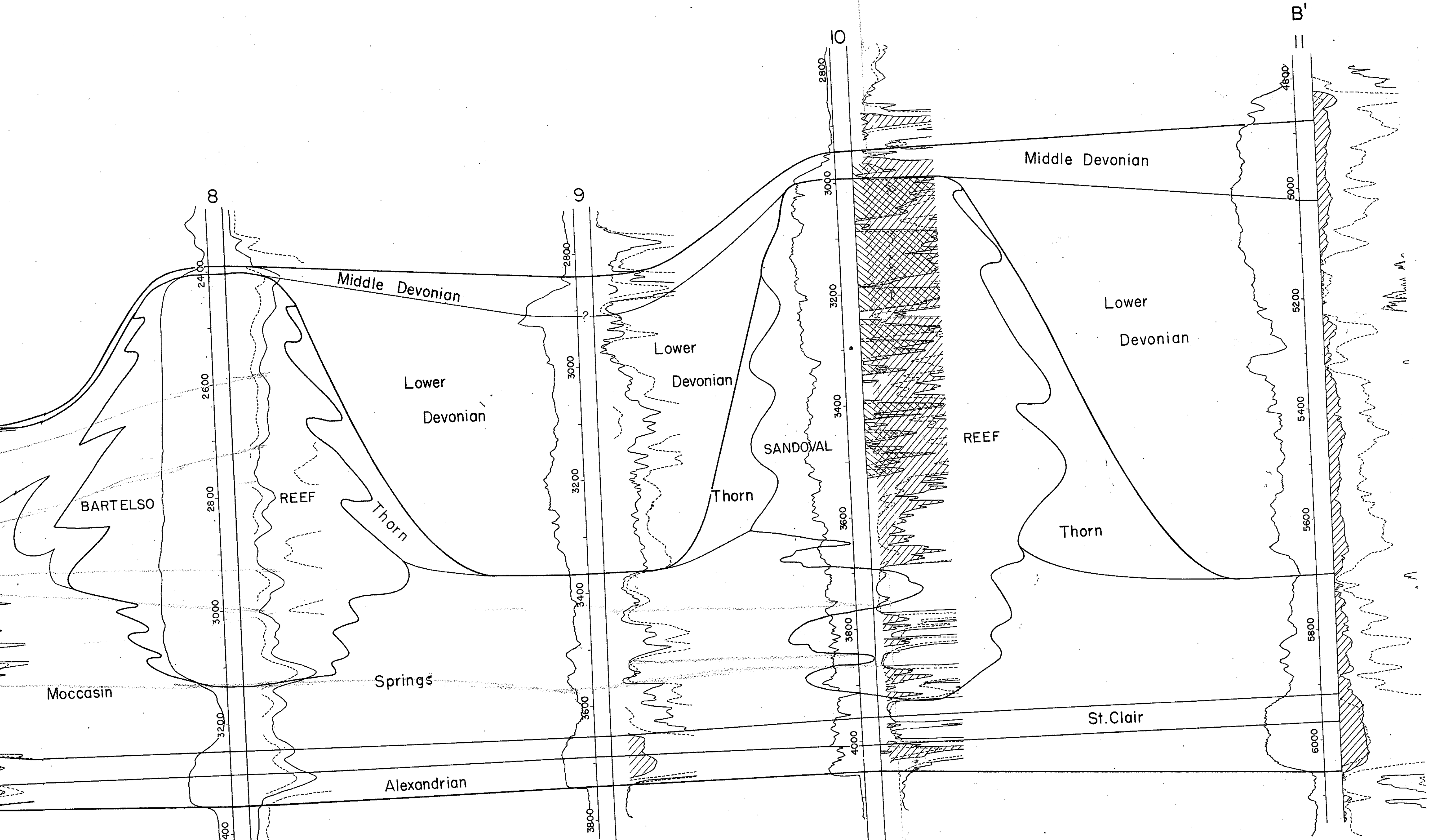
The Pray 1 Baker well, sec. 17, T. 18 N., R. 6 E., Piatt County, penetrated a section of reef core, with outwash above and below. Numerous wells in the LaSalle anticlinal belt from Coles County north penetrated reef core, outwash, or both.

The map (fig. 6) showing reef distribution indicates other occurrences in which the evidence of reef proximity is doubtful, consisting only of unusually pure limestone or dolomite, whose relative purity may be due to admixture of reef-derived carbonates, or may indicate only normal sedimentary variations.

Possibilities for oil production from Silurian rocks other than the Niagaran reefs may be summarized briefly. Reservoirs of low permeability and consequent light oil or gas production may be developed in a number of Niagaran and Alexandrian rocks by post-Niagaran erosion and weathering. Suitable structural or stratigraphic trap conditions have localized pools within the belt where pre-New Albany erosion has laid bare the Silurian rocks. Oil production at Mount Auburn in Christian County, Collinsville in Madison County, oil shows in the Silurian of Sangamon and Morgan counties, and gas production at Pittsfield, Pike County, are of this type. It is to be expected that similar light production will be found in the future in the region of west-central Illinois in which the Niagaran is less than 250 or 300 feet thick (fig. 4).

[50] Lowenstam, H. A., op. cit., Marine pool, fig. 7.

Illinois State Geological Survey
Report of Investigations No. 145
1949


B'
8
9
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11
Middle Devonian
Middle Devonian
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SANDOVAL
REEF
Moccasin
Springs
St. Clair
Alexandrian
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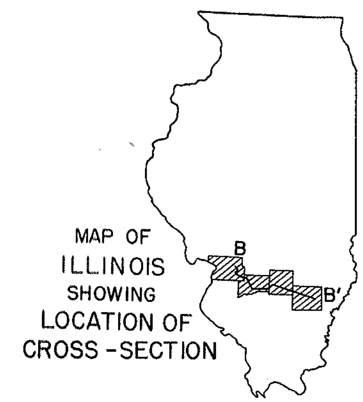
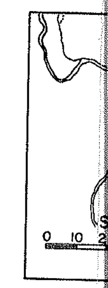
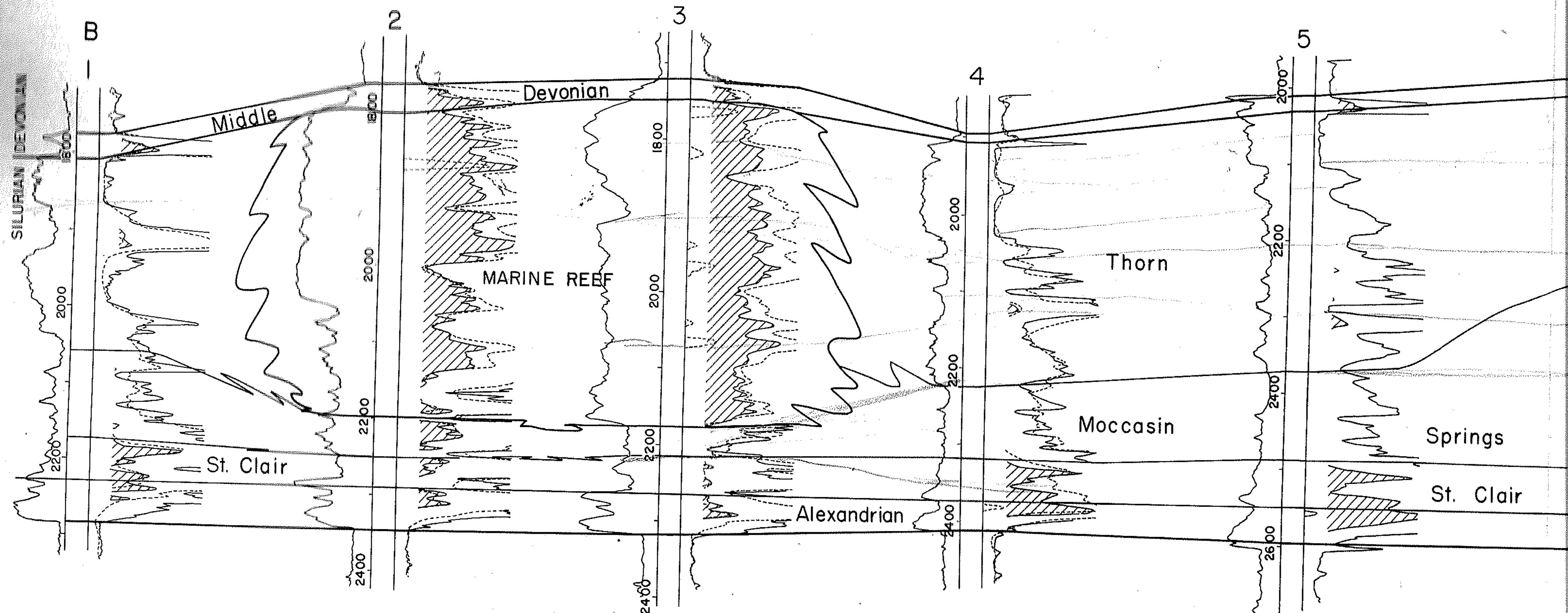
6000

WELLS IN THE SECTION

NO.	COMPANY	FARM	SEC.	TWP.	RANGE	COUNTY
1	POWERS	NO. 1 KAUFMANN-ISENBERG	21	5N	6W	MADISON
2	SLOAN & RYAN	NO. 1 KISNER	2	4N	6W	,,
3	EASON	NO. 1 MAYER	15	4N	6W	,,
4	THOMPSON	NO. 1 REYNOLDS	36	4N	6W	,,
5	MAGNOLIA	NO. 1 PLOCKER	10	3N	5W	,,
6	TATUM	NO. 1 SCHRAGE	17	3N	4W	CLINTON
7	EASON	NO. 1 SCHUETTE	3	2N	4W	,,
8	MOSEBACH	NO. 1 SCHLARMANN	9	1N	3W	,,
9	GULF	NO. 5 BUEHLER COMM.	1	1N	1W	,,
10	MARTIN	NO. 1 ROBINSON	4	2N	1E	MARION
11	PURE	NO. 3 BILLINGTON	27	1N	7E	WAYNE







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