been produced within historic times by differential erosion of the indurated breccia. The complete removal of less resistant rock through the center of a stack produced a natural bridge—the famous Arch Rock (pl. XVIII).

However, the shape of some caves invalidates this theory of origin. A few caves were found which extend downward into the breccia and pinch out with depth. A cave in breccia in St. Ignace State Park, on the bluff above Graham Street, extends inward and downward for a distance of about 30 feet. These caves could not have been formed by physical erosion, as the rock fragments could not be sluiced out by moving water. They were formed by chemical activity (solution), or they are large interstices between the slabs of rock composing the breccia.

The famous Crack-in-the-Island which can be seen in various places on the upland of Mackinac Island is a joint crack in breccia which has been widened by solution.

The indurated breccias are a conglomeration of rock fragments of every degree in size. The interstices between the larger fragments are filled with smaller fragments which range downward from a few inches to dust size. The whole mass is firmly cemented together by calcium carbonate precipitated between the rock grains, from ground waters.

The relatively high elevation of all but the north end of Mackinac Island and of parts of the St. Ignace peninsula is due to the resistance to erosion of the indurated breccia. Absence of indurated breccia on nearby Round and Bois Blanc Islands and at the northern tip of the Southern Peninsula permitted erosion to reduce those areas to a much lower elevation. Therefore Mackinac Island owes not only much of its scenic attractiveness but also its superb viewpoints to indurated Mackinac breccia.

NON-INDURATED BRECCIA: The non-indurated breccia is quantitatively much more important than the indurated. Its total volume is enormous. In spite of this fact, it apparently was not recognized as breccia by earlier geologic investigators in this area. Most of the non-indurated breccia is porous and no doubt was penetrated by percolating waters, but these waters did not carry sufficient calcium carbonate to cement the rock firmly together. As a matter of fact, partial induration occurred in many places and various gradations can be found between completely incoherent material and indurated breccia. In this discussion breccia which is

[7]In many places non-indurated breccia is piled in long ridges and has been used for road building. The ridges are beach ridges of the ancient glacial lakes built by waves and currents which moved and piled up the unconsolidated fragments. *Editor.*

not sufficiently cemented to stand out as a resistant rock is classified as non-indurated.[7]

Another type of non-indurated breccia is composed of dolomite fragments imbedded in a matrix of shale. The amount of shale is sufficient to make the rock relatively impermeable. An illustration of this type of breccia is at the south end of the ferry mole cut where the sides of the excavation are much less steep than they are to the north. The material composing the walls looks like mantle rock, but when dug into is found to consist of dolomite in fragments of varying shape and size in a shale matrix. Another good illustration is at the shale quarry one-half mile south of British Landing, on the west side of Mackinac Island. Exposed in different parts of that quarry are: (1) about seven feet of undisturbed red and green shale at the north end of the quarry face; (2) highly disturbed shale with no bedding discernable; (3) the same shale but having a few blocks of dolomite two feet across scattered through it; and (4) typical breccia, with smaller dolomite fragments in a shale matrix.

Elsewhere in the ferry mole cut, between blocks of the megabreccia, masses of trans-formational breccia show various degrees of induration. Farther north, along U. S. Highway 2, between St. Ignace and West Moran Bay, the low banks beside the highway contain poorly indurated cherty breccia. Much farther to the north, in the vicinity of Allenville, where the greenish shale of the Pointe aux Chenes is the normal country rock, "haystacks" of poorly indurated breccia dot the fields and pastures over several sections. These rock mounds consist of slabs of varying size of limestone and dolomite. Many are highly fossiliferous Bois Blanc fragments.

RELATIONSHIP OF BRECCIAS TO EACH OTHER: The intra-formational breccia always occurs in blocks in the megabreccia. Sufficient examples have been described of the juxtaposition of megabreccia blocks to trans-formational breccia to emphasize the point that they are invariably associated together, and without doubt they originated from the same cause and through allied processes. Mackinac Island and the entire St. Ignace peninsula south of the approximate latitude of Allenville (figs. 1, 2) are built of a mixture of megabreccia and trans-formational breccia. On Round and Bois Blanc islands, however, and on the south side of the Straits in the Southern Peninsula the trans-formational breccia is decidedly subordinate to the megabreccia.

The megabreccia and the trans-formational breccia can be viewed together in the ferry mole cut, at Castle Rock, on St. Ignace Peninsula, and south of Dwightwood Spring on the east side of Mackinac Island. Castle Rock itself is indurated trans-formational breccia, but, the upland immediately to the west, on which the lower end of the viewpoint gangway is footed, is composed of megabreccia. The block nearest Castle Rock has a dip to the west of 17° but where it abuts against the indurated breccia the dip increases to 45° and the rock at the end of the abutting layers is brecciated in places. The evidence at this locality points toward the dropping of the megabreccia block after the trans-formational breccia was in place, with the bedded rock dragging along the contact.

At the cliff south of Dwightwood Spring on Mackinac Island, the bedded rocks which lie in front of, and abut onto, indurated breccia have a dip of 19° to the southwest and obviously belong to a block in the megabreccia. Although no drag was found where these massive beds approach the indurated breccia, a tendency to brecciation in the contact zone was observed.

AGE OF BRECCIATION

Obviously the brecciation took place after lithifaction of the rocks involved. In no other way can the angular blocks of bedded rock of widely varying age be explained. Because Bois Blanc rocks are recognized in practically all of the breccia examined, it can be concluded that brecciation was at least post-Bois Blanc. However, Detroit River rocks are thought to be in the Bois Blanc-containing breccias of the St. Ignace district, and the occurrence of Detroit River rock in the breccia near Rogers City cannot be doubted. In the north end of the quarry of the Michigan Limestone and Chemical Company at Calcite the Dundee has been completely removed. At this place a large pit has been excavated in the floor of the quarry, and breccia consisting of dolomite fragments of varying size in a blue clay shale matrix is exposed. Although this pit is almost filled with water, the uncomformable contact between the flat-lying bedded Dundee limestone and the underlying breccia can be seen and examined a short distance above water level on the west side of the pit. A large dolomite mass weighing many tons, and smaller dolomite fragments, have been dredged out of the harbor slip at the port of Calcite. Company officials report that these dolomite masses are likewise embedded in blue clay in the lake bottom. Furthermore R. A. Smith[8] states that in 1914 breccia was exposed on the beach at Calcite in the area now covered by the plant's tailings pile. This site has the same elevation as the upper surface of the breccia in the deep pit, which is three or four feet above the lake level. Smith also reports that he visited a core test well drilled in 1914 southwest of the quarry which was 800 feet deep and had penetrated a large amount of breccia beneath the Dundee.

[8]Informal communication.

The age of the brecciation at Rogers City is undoubtedly post-Detroit River and pre-Dundee. It is likely that the brecciation in the immediate vicinity of the Mackinac Straits is of the same age, but it is admitted that the process of brecciation could have been a continuing one over a considerable period of time and that some of the brecciation might have taken place earlier.

ORIGIN OF MACKINAC BRECCIA

Naturally the breccia deposits of the Straits region have excited the curiosity of all geologists who have visited the area. The rocks of Mackinac Island have been most discussed, not only because of the good breccia exposures but also because this island has long been a stop-over point for travelers on the lakes. Many hypotheses have been advanced to answer the problem of the breccia. A theory of its origin reached after field studies (1942-1944) of recent and old exposures is herewith presented.

PREVIOUS HYPOTHESES

At least nine geologists have described the Mackinac breccia in print, and eight have ventured explanations regarding its origin. John J. Bigsby, British army doctor by vocation and geologist by avocation, who visited Mackinac (then called "Michilimackinac") Island in 1819 and again in 1820, first described the rocks as follows (1821):

> "The rocks are calcareous; and the clear idea of their nature is afforded by the south-east extremity of the north-east precipice which may be described as follows: A few soft strata, very thin, white and horizontal, shew themselves at the top; but below this the limestone becomes yellow and ragged. Much of it is compact, but it is more usually occupied by vesicles (as from bubbles of air) encrusted with crystals of quartz in botryoidal clusters. A few of them are three or four feet in diameter, and contain smaller cavities in several series. Other parts contiguous to this, are an aggregate of angular fragments of slaty limestone cemented as if by semifusion, and with interstices lined with quartzose crystallizations. The size of the fragments varies from one to eight inches. They also are of an ochry yellow. The bottom of the cliff is in horizontal strata, which are moderately thick, very soft, even so as to write, and of a white, or bluish color. I have been thus minute, on this spot, as the herbage does not permit an examination at any other except in small patches where similar appearances were noticed.
>
> "The north-west half of this long side of the Island declines in height very gradually and consists of debris excepting a few schistose strata at the top. Not far from the end a road is making up the steep (1810).

Here the limestone contains a few blue and white striped flints, which are remarkable for being broken, small, and angular. . . .

"The other long side possesses the same geological features as the one described. The breccia perhaps abounds more here. The slaty portions are found at *every level* and at one place in strata two feet thick. About the middle there is a cave, about three yards in its greatest depth, formed by the concurrence of several of the cavernous bowl-shaped hollows, thus creating one of great dimensions; whose interior is subdivided into smaller cavities seriatim.

"The beach is covered almost exclusively with limestones, slaty, vesicular, and brecciated. . . .

"Two, if not three eras and modes of formation are here clearly distinguishable. The first and oldest is the slate, which is seen to floor the lake for miles around. Upon it are supported two calcareous masses which mingle with each other and with short slips of the schist in the greatest disorder; and having a few of the broken flints interspersed. In all probability they are veins of strata which have been overwhelmed by a sudden violent force.

"Heat may have been the means of raising, comminuting, and partially melting this bed of limestone. Steam, a principal agent, may have insinuated itself into the more yielding portions; and the whole, has finally consolidated."[9]

It is curious that in a slightly later but very similar paper Bigsby[10] omitted the concluding paragraph, in which a possible mode of origin is suggested. He does, however, in the later paper, compare the "cavernous and brecciated" limestone of Mackinac with the magnesium breccia of Bristol and other parts of England.

The second annual report (1839) of the first State Geologist, Douglass Houghton, contains some keen observations on the Mackinac breccia and a conclusion as to its possible mode of formation:

"The shattered and deranged condition of the rock upon the island of Mackinac, and its vicinity, gives the whole mass a peculiarly complicated structure, and has led to what is conceived to be an error respecting it. Thus the rock has been described as a conglomerate, destitute of stratification, a conclusion which would appear to have been drawn without proper consideration of the facts connected with the subject. That the fragmentary masses, composing the main portions of the rock, have not been transported, is conclusively shown by the fact that the most delicate angles are preserved, a circumstance which could not have taken place had they been subjected to the action of water, before being cemented. A careful examination has shown that portions of the rock still remain, in which the relative position of the original lines of stratification are preserved for an extent of several rods; and on Round Island the line of stratification was traced for a distance of nearly half a mile.

"The rock in question, no doubt occupies very nearly its original relative situation, and its present condition may be ascribed to an uplift of the strata, subsequent to the complete induration of the rock; a cause which is amply sufficient to account for the present appearances. The fragments thus separated have been imperfectly cemented by the gradual infiltration of calcareous matter, thus re-uniting the complete mass."[11]

Twelve years later James Hall, noted New York State Geologist, described the breccia in a paper published in the Government report prepared by J. W. Foster and J. D. Whitney. Hall tentatively suggested one method of formation in his description, and, in a footnote, by analogy, suggested another method.

"Returning, for a moment, to the island of Mackinac and the more elevated positions of Pointe St. Ignace and Gros Cap, we find the marly beds succeeded by a brecciated limestone, composed of what appears to be thin argillo-calcareous beds, or laminae, which often partially, or entirely, indurated, have been broken up and mingled with a softer argillo-calcareous mud. It may be very appropriately termed a brecciated limestone.* This brecciated mass, in its lower parts, is composed of broken, thin-bedded limestone, like the higher layers of the Onondaga salt group, of the thinly laminated beds connected with the gypsum deposits of New York and Canada West, which have been recemented by a calcareous mud. The fragments are presented in every possible attitude, as if broken up by the action of conflicting currents, though I was unable to detect the effects of anything like wearing action upon their edges."[12]

*The aspect of this rock is very similar to what may be seen, on a small scale, in countries where calcareous springs are abundant. The thinly-laminated and shaly limestone mingled with others of a more massive character, being broken up, becomes cemented together by the calcareous deposit from the springs, and forms a mass not unlike some portions of this limestone.

The second State Geologist, Alexander Winchell, visited Mackinac Island in 1860. He described the breccia as follows:

"The well characterized limestones of the Upper Helderberg Group, to the thickness of 250 feet, exist in a confusedly brecciated condition. The individual fragments of the mass are angular and seem to have been but little moved from their original places. It appears as if the whole formation had been shattered by sudden vibrations and unequal uplifts, and afterwards a thin calcareous mud poured over the broken mass, percolating through all the interstices, and re-cementing the fragments."[13]

The first completely detailed observations on the Mackinac breccia were published by the third State Geologist, Carl L. Rominger,[14] in 1873. He recognized the breccia as composed of "a great variety of calcareous, dolomitic, cherty, and calcareo-argillaceous rock fragments, mixed and thrown about through the re-cemented rock mass." Rominger was the first geologist to call attention to the regional nature of the breccia, noting that rocks of similar age are brecciated on several of the islands in Lake Erie.

With most of Rominger's observations the writers have no arguments. But we cannot agree with his statement that layered dolomites underlie the breccia, inasmuch as we have found that layered rocks lie at a lower elevation than some cliff breccia exposures, but are in front of, and are truncated by, the near-vertical breccia masses. The writers also differ with two points in Rominger's interpretation. Rominger believed the breccia to be composed in part of the fractured beds of the immediately underlying formation

[9]Bigsby, John J., "Geological and Mineralogical Observations on the Northwest Portion of Lake Huron,": Am. Jour. Sci., 3, pp 268-9, 1821.
[10]———————, "Notes on the Geography and Geology of Lake Huron," Geol. Soc. London, Trans. (2), 1, p. 194, 1824.
[11]Houghton, Douglass, Documents, House of Representatives, State of Michigan, p. 389, 1839.
[12]Hall, James, Upper Silurian and Devonian Series: Geology of the Lake Superior Land District, Pt. II, U. S. 32 Cong. Spec. Sess. Ex. Doc. 4, p. 162, 1851.
[13]Winchell, Alexander, First biennial report of the progress of the geological survey of Michigan, Lansing, 1861, p. 61.
[14]Rominger, Carl, Paleozoic rocks (Upper Peninsula); Michigan Geol. Survey, vol. I, pt. 3, pp. 22-28, 1873.

and that the large vertical slabs of higher rocks in the breccia tumbled into clefts during the present erosion cycle. However, the latest discovered evidence indicates that the source rocks were from upper formations and the writers found that large vertical blocks are an integral part of the breccia.

It is surprising to note that, in spite of his detailed observations, Rominger did not offer any explanation of the genesis of the breccia in his published reports.

Twenty-two years later A. C. Lane, later State Geologist, proposed a theory to explain both the breccia and the salt deposits:

"The period of the Monroe beds is that of the Salina and Lower Helderberg. At that time Michigan was covered by an excessively salt sea which stretched from Wisconsin to New York, was bounded by a continent on the north and east, on the west by low land in Wisconsin (the edge of the Helderberg is found barely extending to just north of Milwaukee), and on the south by a great bar, or reef, or flat in Ohio, which seems to have been just awash. This is indicated by the prevalence in the Ohio Helderberg, not only of ripple-marks, but also of mud cracks and of brecciated and conglomeratic layers. If we imagine tides like those of the Bay of Fundy rushing over this flat, producing this breccia and conglomerate and bringing fresh supplies of water to the enclosed sea, and furthermore that the sea was exposed to a hot sun and received but little accession of fresh water from rivers—this latter is shown to be true by the scarcity of mud and sand—we have the conditions of the Helderberg or Monroe deposits, conditions which are evidently favorable to the formation of a sea charged with salts."[15]

According to such an hypothesis, horizontal rather than vertical breccia deposits would be produced. It must be noted that Lane was primarily discussing the Monroe County breccias, not the breccias of the Mackinac Straits region.

I. C. Russell published a report in 1905 on a reconnaissance trip made the preceding year along the north shore of Lakes Michigan and Huron. Although primarily interested in the Pleistocene and recent history of the shoreline areas, Russell observed the breccia and developed a logical hypothesis for its origin:

"The rock, mostly impure limestone, at the top of the gypsum bearing formation and marking the passage into the overlying formation, is peculiar, inasmuch as it consists of angular fragments of limestone inclined in all directions and cemented into a compact mass by carbonate of lime which has been deposited in the cracks and crevices between them. This breccia is well exposed in the rocky ridges in the western portion of the town of St. Ignace, and at the 'Sugar Loaf' and other localities on Mackinac Island. An explanation of the origin of the breccia, so far as I am aware, has not been offered, although Hall directed attention to it and judging from the statements made in his report, seemed to consider it as evidence of an unconformity, that is, the occurrence of an interval during which the lower formation was exposed to the air and broken and eroded before the rocks resting on it were deposited. The fragments of limestone in the breccia, however, are sharply angular and not rounded as is nearly always the case with stones that have been weathered, or removed and

[15] Lane, A. C., The Geology of Lower Michigan: Michigan Geol. Survey, Vol. V, pt. 2, p. 27, 1895.

re-deposited by water. The nature of the breccia and its occurrence above strata containing easily soluble beds of gypsum,—and of anhydrite which in the presence of water is prone to change to a hydrous condition, accompanied by an increase in volume—suggests that the fracturing and displacement of the rocks may be due to the removal of material in solution, and to changes in volume caused by the hydration of the anhydrite. Remembering that the present surface of the St. Ignace Peninsula, etc., has been exposed owing to the removal of very considerable depths and probably many hundreds of feet of rock, it is evident that the solution of beds of gypsum or the alteration of the anhydrite, at any time subsequent to the consolidation of the formation resting on it, would lead to movements, and particularly the settling and fracturing of the rocks above the gypsum-bearing layers, which would become broken, and displaced and if re-cemented would form a breccia. The above suggestion may perhaps lead future visitors to the region about Mackinac to examine the rocks attentively with the view of discovering evidence which will sustain or disprove the hypothesis here proposed."[16]

This was the first expression of the possibility of brecciation by collapse. It will be shown later that leaching of salt is a more probable cause than the solution of gypsum.

An odd hypothesis was presented by Grabau in 1913:

"THE MACKINAC LIMESTONE BRECCIA. This is a remarkable example of a breccia made up of large and small angular fragments of finely bedded upper Siluric (Monroan) limestones and dolomites, derived from a still intact cliff of this limestone near St. Ignace in the Upper Peninsula. The deposit is best seen in the cliffs of Mackinac Island, nearly the entire mass of which seems to be composed of this rock, which must here have a thickness of between 200 and 300 feet or more. The fragments are of all sizes from that of a pinhead to blocks ten feet or more in diameter, and their position in the breccia is such that the stratification lines of the individual blocks dip in all directions. The distance to which these blocks have been carried from the parent ledges is many miles, and the width of this ancient stream is unknown. At St. Ignace the high ground behind the beach consists of the Monroe dolomites in undisturbed horizontal position, but in front of these at a level represented in the cliffs by bedded strata are erosion stacks of the brecciated rock, carved from the cliff during a period of higher level of the lakes. The position is such as to indicate that these stacks are evidently a part of the rock stream, while the cliffs behind the stacks are a part of the original cliff. In one part of Mackinac Island the breccia is found to be underlain by shales and thin limestones of Monroan (or Salinan?) age.

"That the rock stream represented a subaerial flow of the rocks is shown by its character. Fine, rounded quartz grains, blown from a distance, are incorporated in the mass. The age of this stream is Lower Devonic, the Middle Devonic Onondaga strata enveloping and enclosing it and partly incorporating it as a somewhat reworked product."[17]

The writers take decided issue with Grabau's statement that shales and thin limestones underlie the breccia on Mackinac Island, as excavation has proved that the sedimentary rocks abut against the breccia. We disagree with his description of dolomites in "undisturbed horizontal position" in the cliff at St. Ignace, since careful examination proves that the cliff back of St. Anthony's Rock

[16] Russell, I. C., A geological Reconnaissance along the North Shore of Lakes Huron and Michigan; Report of the State Board of Geological Survey of Michigan for the year 1904, pp. 44-45, 1905.

[17] Grabau, A. W., Principles of Stratigraphy, New York, 1913, pp. 547-8. Abstract in Science, n. s., 25, 295-6, 1907.

at St. Ignace does not contain "undisturbed" dolomite,—it consists of both unindurated breccia and tilted slabs of megabreccia.

In the writer's opinion the first plausible hypothesis on the origin of the Mackinac breccia was developed by Hindshaw and reported by Smith in 1914:

> "During the past few years Mr. Henry H. Hindshaw, former assistant State geologist of New York, has made an extensive study of the limestone deposits of possible commercial value in Alpena and Presque Isle counties. He observed the abnormal dips, local fractures, and the brecciation of the Dundee limestone, which near Rogers City, is so great that drilling with a core drill is very difficult.
>
> "In the Salina, in Alpena and Presque Isle counties, the salt beds aggregate 300 to 800 feet in thickness. According to the upward rise of this formation toward the northeast and east, it should form the bottom of the Lake Huron basin. Thin salt beds occur at Manistee and Ludington, and here too are to be observed abnormal local dips and a 'vesicular' dolomite above the salt which caves in the drillings and is very probably brecciated. The brecciation in the Dundee and the Monroe in the Frankfort well appears to be undoubted.
>
> "In limestone areas, much of the drainage is underground. In the limestone belt of northern Michigan there are relatively few streams as most of the surface waters drain into the numerous sinks. The Dundee, especially near its base, and the Monroe beds are very heavily water bearing, being filled with crevices, fissures, caverns, and underground water channels. The water channel struck in the Detroit salt shaft was more than five feet across. In many instances drill tools suddenly drop four or five feet into cavities. Again, in drillings, beds of dolomitic sand are struck in the Monroe which flow into the drill holes like thin mud. Such sands and oozes may be the residuum of other beds carried away by solution.
>
> "Mr. Hindshaw related these facts—the abnormal dips, the brecciation of the Dundee and the Monroe beds, the large underground water circulation, the oozes, the relation of the margin of the Salina formation to the basins of Lakes Huron and Michigan, and conceived the idea that these lake depressions are due in part to the ablation, or solution of the salt in the Salina and that the brecciation was caused by the slumping incident to the removal of the salt beds below. While the validity of all of the evidence has not been investigated, the theory as advanced contains elements of plausibility and is worthy of consideration.
>
> "It is obvious that if the salt in the outer edges of the formation should be removed by solution, there would be slumping in the beds above, which might very possibly cause brecciation in rocks like dolomites and limestones. The slumping would also explain the abnormal dips, observed near the lake shores."[18]

Since Hindshaw's time quarrying operations in the Calcite quarry of the Michigan Limestone and Chemical Company have exposed the unconformable contact between the Dundee formation and the underlying breccia. Brecciation does not extend into the Dundee; the irregularities in the Dundee rocks can be explained by post-Dundee settling. The collapsing which produced the breccia must have taken place before the Dundee formation was deposited.

Norton[5] classified the Mackinac breccia as "founder" breccia, based on personal observation which he found supported the theory

[18]Smith, R. A., The occurrence of oil and gas in Michigan: Michigan Geol. Survey, Pub. 14, pp. 206-7, 1914.

of Hindshaw. An additional observational fact reported by Norton is the presence of small chimneys of breccia penetrating the shales at the foot of the cliffs on Mackinac Island.

Newcombe, in his monograph on the Michigan Basin, mentions salt leaching as a factor in modifying structural features:

> "Faulting which is caused by the dissolving of salt beds is probably a widespread type of displacement in the rocks of the State. The margins of the Detroit River and Salina salt basins . . . are general belts of extensive solution and slumping resulting from that cause."[19]

SUGGESTED THEORY

The theory developed by the writer of this report is in its main essentials the same as the theory advanced by Hindshaw. The observations made in the field and in the study of the well samples strongly support this theory.

The first stage in the sequence leading to the formation of breccia was the deposition of the rocks belonging to the Point aux Chenes formation. The land surface, floored with rocks of Niagaran age, was submerged beneath the Pointe aux Chenes sea. While this submergence was in effect, several hundreds of feet of shale, dolomite, salt, and gypsum were deposited. According to well records, salt of Pointe aux Chenes age underlies the Southern Peninsula of Michigan excepting beneath the northern tip and the southern and southwestern parts. It is also in southwestern Ontario. The thickest salt deposits, over 1600 feet, are found immediately west of Saginaw Bay, but as much as 1200 feet is found as far north as northwestern Alpena County. According to the theory, salt was originally deposited in the Pointe aux Chenes rocks farther north than the present northern boundary of the salt so that the present St. Ignace peninsula was also underlain by salt. It is also possible that the salt beds in the southeastern corner of the State originally extended into northern Ohio.

During times of subsequent submergences of the land in the Straits area, the St. Ignace dolomites, the Bois Blanc dolomites, cherts, and limestones, and the early Detroit River dolomites and limestones were deposited in successive layers above the Pointe aux Chenes salt-bearing rocks.

This sequence of deposition was followed by emergence. Perhaps during earlier emergences, but certainly during the time following the early Detroit River limestone and dolomite deposition, percolating underground waters leached great quantities of salt

[19]Newcombe, R. B., Oil and gas fields of Michigan: Michigan Geol. Survey, Pub. 38, 1933, p. 118.

from around the rim of the salt basin. A vast series of caves and caverns were produced where the Pointe aux Chenes salt lay above the ground water table. Presumably the water below the ground water table level was so saturated that further solution was not possible. Because of the basinward dip of the sediments in the Southern Peninsula, the salt available for leaching was only around the edges of the basin.

Naturally the formation of large caves underground created a condition of instability leading to the collapse of the cavern roof. The field evidence strongly suggests that this collapse was of two types. In one type the collapse was local and probably sudden. The overlying shale, dolomite, limestone, and chert broke into fragments of varying size and fell and slid downward. Naturally the individual fragments when they stopped falling were in random orientation and fragments from different rock layers were jumbled together. In this way the transformational breccia was formed. The probable result of local collapse was a sink at the surface.

The other type of collapse occurred between the areas of local and complete collapse. In these larger areas roof failure on a regional scale caused great blocks of sedimentary rocks to drop downward. Invariably one end of the block fell farther than the opposite end, producing a tilt. In this way the megabreccia was produced. Two observations suggest that the dropping of the large blocks took place after adjacent local collapse (p. 152). However, in other places the order could have been reversed, or the collapsing could have taken place simultaneously. Also, the let-down blocks may have dropped by stages, successive collapses occurring as additional amounts of salt were leached. It is suggested that most of the collapsing took place during the general period of emergence following Detroit River deposition and preceding Dundee deposition. However, the writer does not intend to imply that collapse was simultaneous throughout the entire area. When a roof cavern could no longer support the load of overlying material it collapsed and no doubt long periods of time intervened between the time of the first and the last collapse.

During and after the collapsing, the forces of erosion operating at the surface smoothed that surface into a peneplane and the surface inequalities resulting from the sink hole or karst topography and the larger depressions resulting from the sinking blocks were destroyed. Eventually in another period of submergence the Dundee sea came in and the limestones of Dundee time were deposited on the eroded surface of the older sediments, which, around

the rim of the basin, had suffered considerable collapse. No doubt some additional settling continued to take place even after the Dundee limestones were lithified as shown by the fractures and minor structures in the Dundee in the quarry of the Michigan Limestone and Chemical Company near Rogers City. Also subsequent to the collapse, ground waters percolating through the jumbled rock fragments in the sink holes gradually cemented much of this material, producing the indurated breccia.

The final chapters in this history include: deposition of younger sediments, the relatively recent erosion history which brought about the exhumation of the collapsed rocks, and partial isolation of indurated breccia masses by differential erosion.

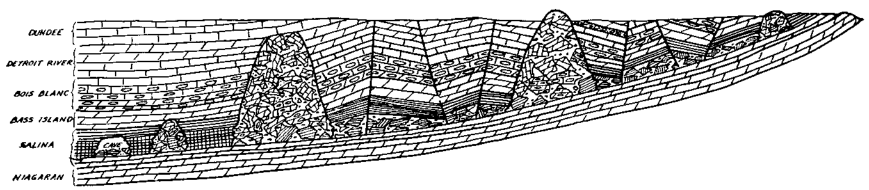


Fig. 3. Hypothetical cross section of the Mackinac Straits Region showing collapsed formations above the Niagara limestone, breccia chimneys, and breccia stacks.

Discussion

The writer believes that the evidence of downward dropping of rock fragments to form the breccias is conclusive. The breccias consist of a mixture of fragments from a stratigraphic section several hundred feet in thickness, and millions of years apart in age of deposition. For the larger blocks composing the megabreccia, the abundant normal faults and slickensides are additional evidence of vertical movements. The vertical nature of the breccia masses denies the possibility that the brecciation could have been produced by any onshore or offshore processes.

Obviously then, if the breccias were the result of downward dropping, the collapse must have been caused by the existence of large openings in the deeper rocks. Pointe aux Chenes is the logical formation in which openings could occur, because soluble rocks are in the formation. Salt and gypsum are soluble, although gypsum does not go into solution as readily as salt. In this discussion the solution of salt rather than of gypsum is emphasized because to produce the phenomena observed, several hundred feet of rock must have been removed and the well records do not show gypsum beds of such aggregate thickness. A second obvious reason for assuming that the collapsing was into caves in the Pointe aux

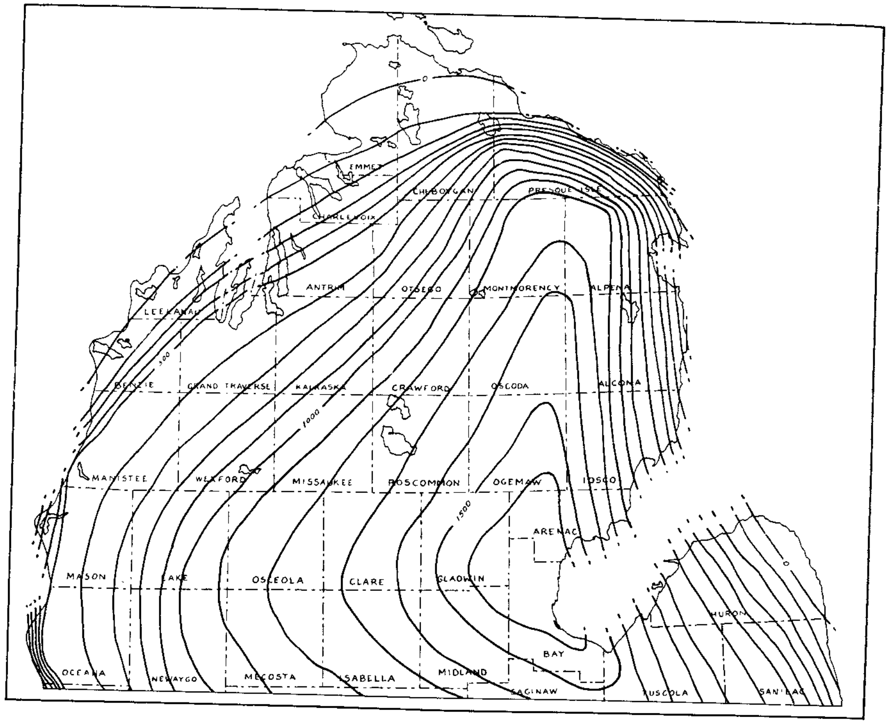


Fig. 4. Isopach map showing aggregate thickness of Salina salt.

Chenes formation is that the collapsing extends down into that formation. No evidence of any such sinking or brecciation is found in the underlying Niagaran and older rocks.

The accompanying map (fig. 4) shows the aggregate thickness of the Salina salt in the northern part of the Southern Peninsula. This map was made from well records. The lines are drawn with an interval of one hundred feet and each line is drawn through points of equal salt thickness. It can be seen from this map that the salt decreases in thickness from 1200 feet to 0 between northwestern Alpena County and Cheboygan. In other words, the salt in the northern part of the Southern Peninsula has a blunt edge. One would expect where salt was deposited in an evaporating sea that thinning of the salt around the edges of the sea would be gradual. The abrupt edge of the salt body lends weight to the belief that this is a leached rather than a natural edge. A similar conclusion was drawn by Phalen[20] for the edge of the salt deposits in one part of New York State.

[20]Phalen, W. C., Salt resources of the United States: U. S. Geol. Survey Bull. 669, 1919, p. 21.

"The Solvay wells, near Tully, south of Syracuse, must be located near the edge of the salt bed, and it also seems clear that the bed does not peter out as it does west of Seneca Lake but that it ends abruptly as though part of it had been removed."

Newland is more specific regarding removal by solution:

"The salt measures, naturally, never appear at the surface. They have wasted away from solution by underground waters, so that now they are only found in strength some eight or ten miles back from their former place on the outcrop, where the overlying strata attain a thickness of 800 feet as a minimum. The collapse of the cover following solution of heavy salt seams has further promoted disintegration.[21]

Naturally one would expect that had such salt solution taken place, areas would remain in which collapse did not take place, due to the small size of the caverns. Numerous drillers' reports mention finding small caves in the Salina formation around the rim of the Michigan salt basin. The log of the Diamond Crystal Salt Company well in sec. 31, T. 5 N., R. 17 E., St. Clair County, records "salt and cavity" from 1610 to 1640 feet, and 146 feet of salt and two salt cavities were logged in a well drilled at Kincardine in Bruce County, Ontario.[22]

It is probably more than a coincidence that features similar to those found in the Straits area and believed to be evidences of collapse occur in other places on the rim of the Salina salt basin. The breccias of southeastern Michigan and northern Ohio, and the 15 degree dips reported in the Devonian rocks in southwestern Ontario[23] are examples of this. Furthermore, heterogeneous samples from wells drilled in northern Michigan near the Michigan and Huron shores strongly suggest that the drill passed through brecciated rocks below the Dundee formation. Rock samples from the well drilled in sec. 8, T. 33 N., R. 8 E., Presque Isle County, are decidedly mixed between the Salina and the Dundee. The Cheboygan (city) well reported "brecciated dolomites" in the "Monroe." The log of the Frankfort well in Benzie County records 150 feet of "black to gray brecciated limestone with hard flinty blocks" in the Dundee. The "flinty" rock suggests that the rock is Bois Blanc rather than Dundee. Other examples of breccias penetrated by drilled wells are given in the chapter on Subsurface Stratigraphy.

To account for leaching a body of salt several hundred feet thick from beneath hundreds of square miles necessitates elevation of the salt-bearing rocks into the zone of active ground water move-

[21]Newland, D. H., The gypsum resources and gypsum industry of New York: N. Y. State Museum Bull. No. 283, 38, 1929.
[22]Harkness, R. B., Natural Gas in 1929: Ontario Dept. of Mines, Ann. Rept., Vol. XXXIX, pt. v, 1930, p. 20, 1930.
[23]Stauffer, C. R., The Devonian of southwestern Ontario: Canada Dept. Mines, Geol. Survey, Mem. No. 34, p. 23, 1915.

ments. Also it is necessary to account for disposal of the saturated brine. We know that the Michigan Basin was in existence in early Devonian time; therefore retreat of the Devonian sea and subsequent land emergence would have brought the salt beds close to the surface around the rim of the basin and into the zone of ground water action.

But to account for and explain the disposal of the saturated brine is a little more complex. According to the writer's theory, the Pointe aux Chenes beds around the rim of the basin were elevated above the ground water table after early Detroit River time, and only the central part of the basin was under water. Such a postulated position of the salt above the water table would permit ground water to percolate downward from the surface and to dissolve salt until it became saturated. Given a continuous supply of fresh water from above, a large volume of salt could be leached out in a relatively short space of geological time. However, such leaching would cause the accumulation of saturated brine having some six times the volume of the salt removed. This is not an impossible volume of brine to be stored underground, but perhaps that storage was not necessary. If the Michigan Basin at this time were also a topographic basin having sufficient relief, the ground water table would intersect the surface in stream valleys around the flanks of the basin; and thus provide an outlet for the saturated brine, which, on reaching the surface, would flow down into the evaporating sea at the bottom of the topographic basin (fig. 5). Thus the theory provides a possible explanation for the salt deposits of the Detroit River group. At the present time the Salina (or Pointe aux Chenes) salt beds around the rim of the Michigan Basin are from 400 to 4,000 feet higher than the younger Detroit River salt beds, doubtless a greater difference in elevation than existed in Detroit River times. But if the Salina salt deposits were no more than 50 feet higher topographically than the basin of deposition of the Detroit River salts during Detroit River time, the hydraulic gradient would be sufficient to produce the transfer. Further support of this thesis is the fact that in the Basin the Detroit River salt is in the upper part of the Detroit River section in beds which are younger than the Detroit River beds around the rim.

An approximation of conditions that may have existed in the Mackinac Straits region in mid-Devonian time is in central Kansas where the eastern edges of westward-dipping Permian salt beds approach the surface. This district has been described by Bass as follows:

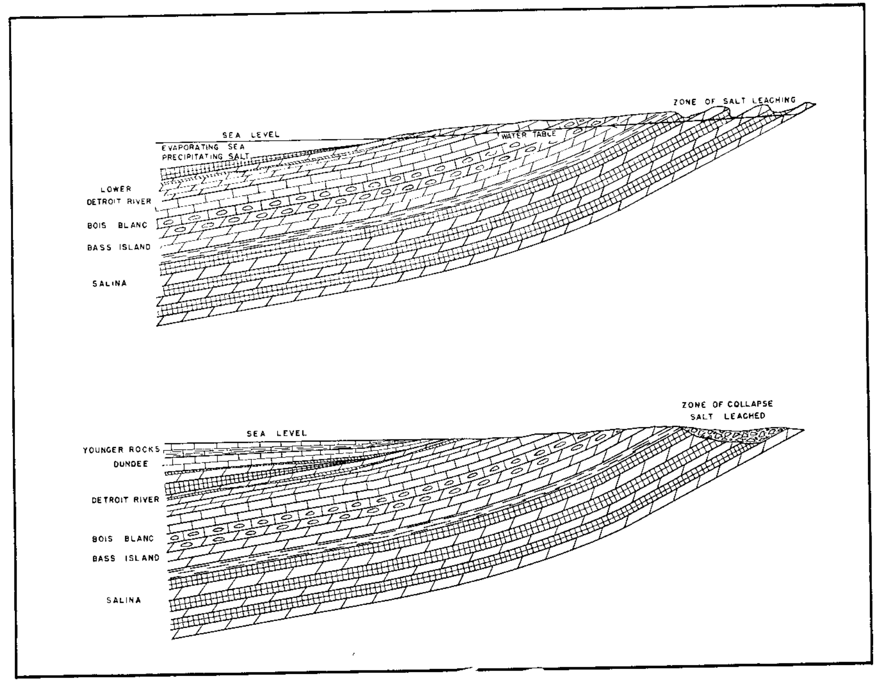


Fig. 5. Diagram to illustrate theory of deposition of Detroit River salt.

"A study of the logs of wells drilled along the eastern margin of the salt area indicates that in the past salt beds extended farther eastward and that the present eastern boundary is largely the edge left by the dissolving away of this eastern portion. Comparison of the records of wells drilled in northern Sumner County on both sides of the margin of the salt shows a marked constriction in the eastern wells of the interval occupied elsewhere by the salt. A similar condition is shown by wells drilled in Lincoln county. Near this eastern margin wells reporting the salt to be more than 200 feet thick are only a few miles west of wells showing no salt. This abrupt change in thickness indicates that the margin of the salt represents an edge resulting from something comparable to erosion, rather than the shore line of an original salt deposit. The constriction of the salt interval in the eastern wells makes it appear very probable that as a result of the leaching and carrying away of the readily soluble salt beds by circulating ground waters near the outcrop, the overlying shale beds settled downward and filled in the cavities. It should be expected that settling on as large a scale as is postulated would be manifest in the topography of the surface, and inspection of the topographic maps that cover the marginal area for the most part corroborates this assumption. A narrow stretch of low-lying land, dotted with marshes, swamps, and lakes, extends northward from northwestern Sedgwick county across Harvey and McPherson counties, practically coinciding with the boundary of the salt area as shown by well logs. The fact that many of these lakes are salty is further evidence that is considered corroborative of the explanation offered.[24]

[24]Bass, N. W., Structure and limits of the Kansas salt beds: Kansas Geol. Survey, Bull. 11, part 4, p. 93, 1926.

Other signs of large scale salt solution in Kansas are evident, in addition to the evidences of leaching cited by Bass. Drillers frequently report caves of considerable size in this area and actual collapse has occurred during historic times.

Apparently the pre-Dundee leaching of the Salina salt around the rim of the Michigan Basin caused the downdip recession of the salt boundary to a point beyond the reach of large scale solution during the present erosion cycle. However, the salt licks and salt springs in Monroe County, and near Saline in Washtenaw County, may be evidence that some leaching is taking place today on the southern rim of the Basin.

Examples of Collapse of Breccia Elsewhere

Collapse or founder breccias have been reported from many localities. The simplest form is the cavern breccia, similar to the breccias near Fort Stanton, New Mexico, described by M. R. Campbell.[25] The first step in the formation of cavern breccia was the solution of limestone by ground water and consequent production of cavities. One cavity described by Campbell is 100 feet long and eight or ten feet high. Then roof spalls filled the cavern with an irregular mass of angular limestone fragments. Finally the limestone fragments were recemented by deposition of lime from calcareous waters into a solid breccia which completely filled the cavern. An older breccia in Missouri has been described by Morse:

> "In one of the quarries in St. Louis County, Missouri, layers superjacent to a mass of coarsely brecciated limestone are bent down in such a way as to reveal the former presence of a limestone cavern. This structure in connection with other features led to the conclusion that the breccia is due to the collapse of the partially dissolved layers and of the cavern roof, and that the coarse breccia in western Illinois may have originated in a like manner."[26]

Breccia near Rochester, New York, ascribed to foundering, has been described as follows:

> "Founder or solution breccia is also represented, although of relative unimportance in comparison with the prevalence of the preceding types. The walls of some of the larger cavities have collapsed, the fissures being healed by calcite, dolomite, barite, strontianite, gypsum, and many other minerals occurring commonly in the Niagaran limestone."[27]

Perhaps the best three-dimensional example of collapse breccia is in the Tri-State zinc district of southwestern Missouri, southeastern

[25]Campbell, M. R., The origin of limestone breccias (abstract): Science n. s., vol. 27, p. 348, 1908.
[26]Morse, William C., The origin of coarse breccia in the St. Louis limestone: Sci. n. s., vol. 43, pp. 399-400, March 17, 1916.
[27]Giles, A. W., Brecciation in the Niagaran limestone at Rochester, New York, Amer. Jour. Sci., vol. 197, p. 353, 1919.

Kansas, and northeastern Oklahoma. Breccia in this area is abundant, and much of it is ore-bearing, as solutions depositing ore minerals used the permeable breccia body as channelways. The breccia is in a thick series of Mississippian cherty limestones in which circulating ground water has produced caverns of various sizes and shapes. The caverns are of pre-ore age and many collapsed before the ore-bearing solutions came in, producing breccia bodies of more or less local extent. Sheetlike bodies of breccia were also produced:

> "When the interbedded limestone in such a series was dissolved, but not replaced, it allowed the chert to settle irregularly, resulting in strong brecciation, in many places completely obscuring the bedding."[28]

Comparison with Mine Subsidence

A review of a part of the voluminous literature on mine subsidence shows some remarkable similarities with the collapse in the Straits region. The character of the collapse in a mining region depends on many factors, but especially in bedded rocks on the dip of the formation and on the shape of the excavation. Initially the rocks in the Straits region were nearly horizontal, so the complications involved in dipping strata do not enter into this problem.

The type of the mine collapse in which a large cavity is involved is different from the collapse produced by mining out relatively thin veins. Mine collapse in large cavities can be seen in mining regions where large and irregular ore bodies have been mined by the block caving method. Removal of the supporting ore causes the roof to fail, and the cavern grows upward into the overlying rock by natural stoping. The result is a "subsidence dome," (the cavern roof) which may eventually break through to the surface:

> "As the rock fragments fall from the top and sides of the dome, a more or less conical pile of rock builds up."[29]

Although not noted in the literature, this cone of broken rock that accumulates beneath the subsidence dome becomes a breccia when the fragments are cemented together. The size and depth of the original cavern determines whether or not the subsidence dome reaches the surface. If the cavern is small and the distance to the surface relatively great, the accumulation of fallen rock will eventually fill the cavern and support the roof, thereby preventing further fall, but will not prevent fissuring and some downfaulting of the rock on the overhanging walls. This explains the unusual

[28]Siebenthal, C. E., Mineral resources of northeastern Oklahoma. U. S. Geol. Survey, Bull. 340, p. 200, 1908.
[29]Rice, George S., Some problems in ground movement and subsidence: Amer. Inst. Min. and Met. Eng. Trans., vol. 69, p. 389, 1923.

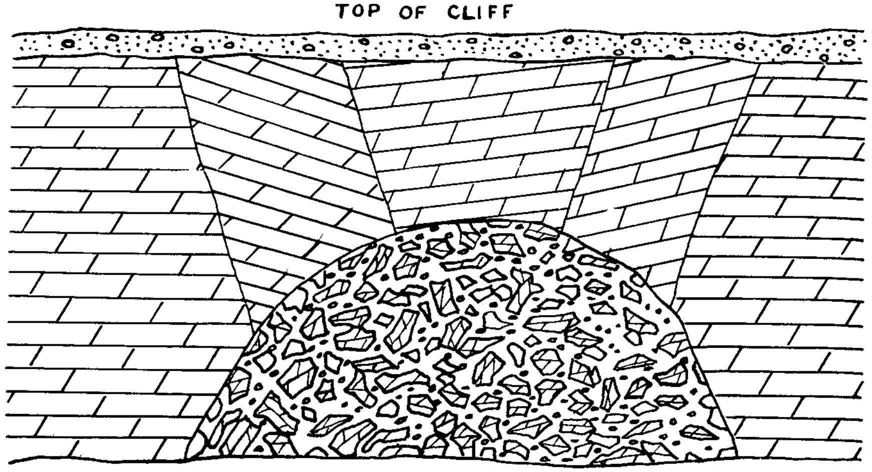


Fig. 6. Diagrammatic representation of exposure of breccia in a cliff on Round Island.

occurrence of breccia on the east side of Round Island (fig. 6). There breccia is exposed on the face of a 20-foot cliff. It consists of brecciated dolomite in a dome-shaped mass which is surrounded and overlain by gently dipping stratified St. Ignace dolomite. This is the only place (except at the Calcite quarry) in the Straits area in which stratified rock was seen above breccia. The rock in the breccia appears to be the same as in the stratified beds. Small faults are common in the bedded rock surrounding the breccia dome. Apparently this is an example of a subsidence dome that failed to reach the surface. A similar dome-shaped mass of breccia overlain by Bass Island dolomites is exposed on the south face of the Holland quarry in Lucas County, Ohio.

Good examples of subsidence domes that break through the surface are found in the Joplin zinc district:

> "Here fossiliferous blocks of Chester, slabs of Pennsylvanian shale, bricks, bottles, and even dead horses are moving down through man-made sink holes and oozing and flowing into man-made caverns. Some day a million or a billion years from now a cross-section of these holes will give some geologist something to think about."[30]

A body of breccia resulting from accumulation beneath a subsidence dome should have a considerable vertical extent and should increase in diameter with depth, which seems to be the condition of the indurated breccia in the Straits region. The non-indurated

[30]Addison, Carl C. Letter dated Oct. 13, 1944.

breccia masses probably have the same origin and the same shape, but because of their incoherent character the walls of such bodies are not exposed over any great vertical distance; therefore it is not possible to check on their shape.

Collapse in an area where a horizontal coal bed has been mined out is quite different. Because most coal veins in collapsed areas are only six or eight feet in thickness, the vertical dimension of the open space is relatively insignificant. It is interesting that collapse occurs not only into the rooms but also in the areas of the pillars due to the failure of the pillars to hold up the roof over any prolonged period of time. Application of this fact effectively cleared up one of the puzzles in the Straits region. It was assumed by the writer that leaching did not completely remove the salt and natural rock pillars remained standing between collapsed areas. Under such conditions the rock above the pillars should be undisturbed, and the writer was perplexed by failure to find any exposures of undisturbed rock anywhere in the collapse district. If coal pillars fail in time, it seems even more likely that salt, with its well-known tendency to flow under pressure, would not long withstand the weight of the overlying rock.

The result of collapse in a mine where a flat horizontal seam is worked by the room and pillar method is a zone of brecciation in the room itself, due to the fragmentation of the rock in falling, but the higher beds may be "let down" with some fragmentation but without complete loss of orientation. It has been noted in a number of coal districts that after the pillars of a coal bed have been robbed and the immediately overlying rock has subsided, higher coal beds, although tilted and fractured and otherwise disturbed, were mineable.

This type of collapse produces what the writer has termed megabreccia. It is presumed that where the salt caves were largest in horizontal dimensions, collapse produced letdown and tilted blocks, but where the caves were of considerable vertical extent, the subsidence dome type of collapse took place. It is possible that both types of collapse might be produced by the solution of a single salt bed—that the first cave leached out might grow upward into the overlying rock by natural stoping and trans-formational breccia be produced, and that while this was going on, ground waters would continue leaching out the salt bed in all directions, and so make horizontal caverns which in turn would collapse and produce megabreccia.

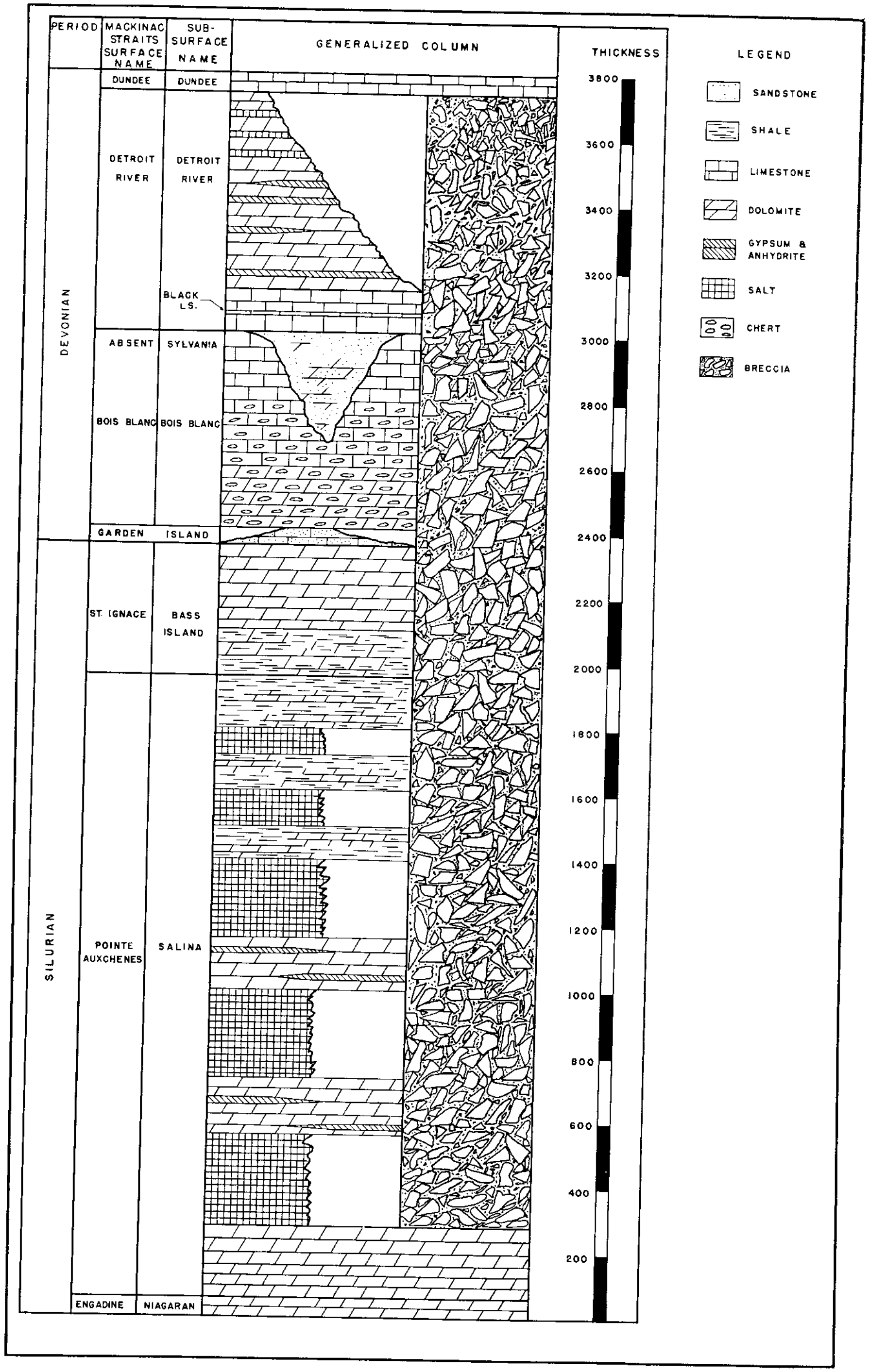


Fig. 7. Generalized columnar section of Mackinac Straits area.

CHAPTER IV

Subsurface Stratigraphy

In discussion of the subsurface stratigraphy of the Mackinac Straits area it should be remembered that the area is the northern rim of a structural basin which was also a basin of subsidence during Paleozoic time, that at times the area was a marine embayment but at other times it was almost cut off from the sea and then became a dessicating lagoon.

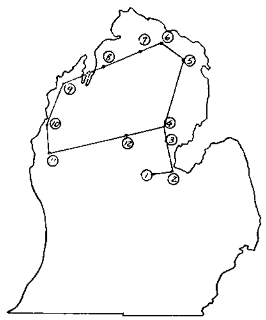
SALINA GROUP

The Salina strata of the subsurface correlates with the poorly exposed Pointe aux Chenes formation of the St. Ignace peninsula. They directly overlie the Niagaran dolomites and are everywhere beneath the surface in the Southern Peninsula of Michigan.

The Salina group is of Silurian age. It probably connects beneath the surface with the New York State Salina by way of the Ontario Peninsula and northeastern Ohio.

The subsurface records of the Salina rocks on the St. Ignace peninsula are poor. Several wells have been drilled in the area and at least two went through the Salina group and into the Niagaran, but evidently no samples were saved from any of these wells. Furthermore, the peninsula south of the approximate latitude of Allenville is all in the collapse zone, and therefore the few well records which are available are confusing. The well drilled in 1887 on the property of the Mackinaw Lumber Company in St. Ignace reported the Niagaran top at a depth of 504 feet, at the base of a 489-foot section of red and blue "slate" with a vein of salt. It is probable, however, that the basal Salinan dolomites were erroneously identified as Niagaran, and the actual Niagaran top is some feet lower than shown by log.

A second well in the St. Ignace vicinity was drilled two miles north of the Mackinaw Lumber Company well. Incomplete samples below 384 feet are available from this well. Between 384 and 600 feet the samples appear to be a mixture of Bois Blanc chert and dolomite, Bass Island dolomite, and Salina dolomite, dolomitic shale, and anhydrite. Fourteen feet of chert and dolomite assumed to have come from the Bois Blanc formation, lies near the base of



NO	COMPANY	FARM	NO	SEC.	T	R	COUNTY
1	DOW	FEE	M2	27	14N	2E	MIDLAND
2	GULF	BATESON	1	2	14N	4E	BAY
3	MAJOR	McTAGGART	1	26	19N	3E	ARENAC
4	PURE	YEO	1	2	21N	2E	OGEMAW
5	TEATER	NEVINS	1	18	32N	6E	ALPENA
6	PRESQUE ISLE DEVEL CO	CHANDLER	1	5	34N	2E	PRESQUE ISLE
7	BROWN	BROWN	1	12	33N	3W	CHEBOYGAN
8	OHIO	CHAMBERLAIN	1	14	31N	8W	ANTRIM
9	LUPHER	WILCE	1	34	28N	14W	LEELANAU
10	RUGGLES AND	RADAMAKER	24	12	21N	17W	MANISTEE
11	WELCH-TAGGART	CAMPBELL	1	16	17N	15W	MASON
12	PURE	THOMPSON	1	3	20N	3W	CLARE

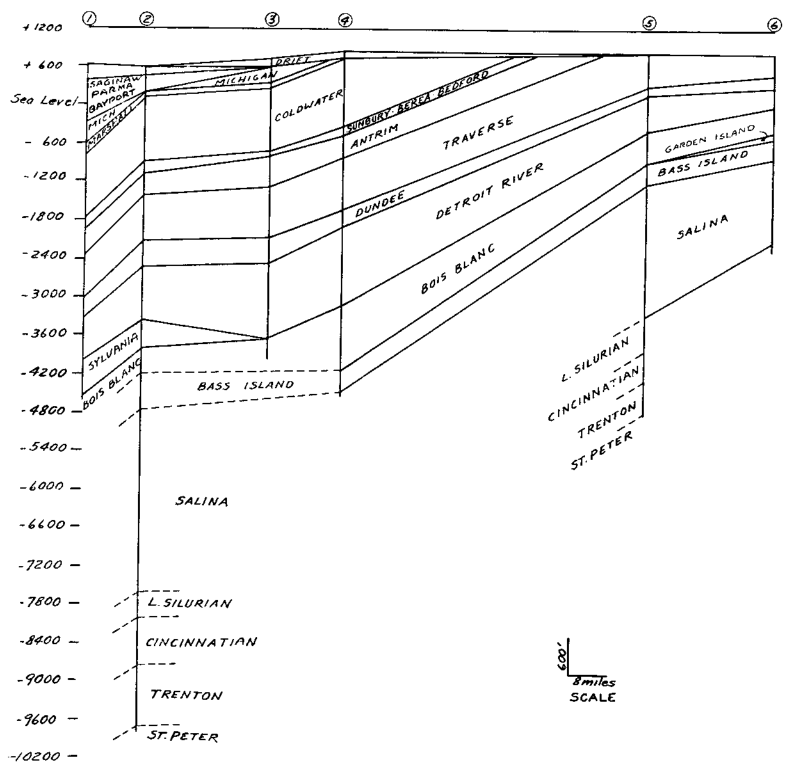
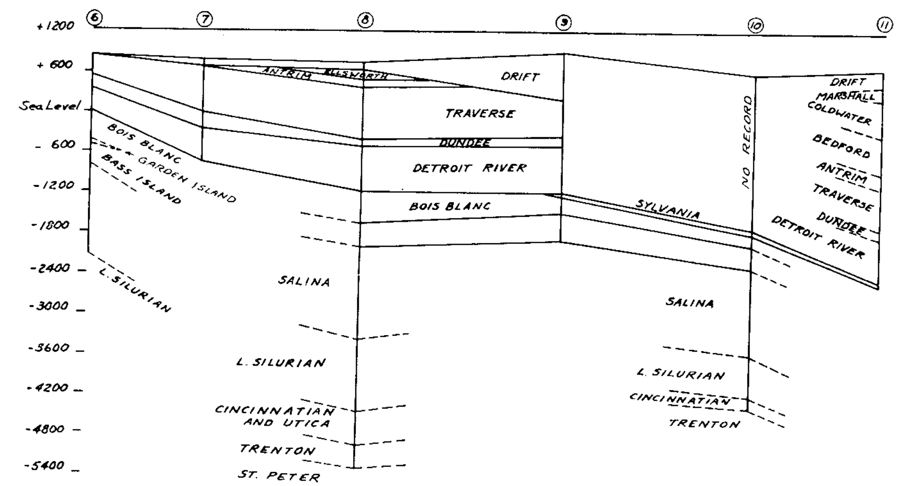


Fig. 8. Cross sections.



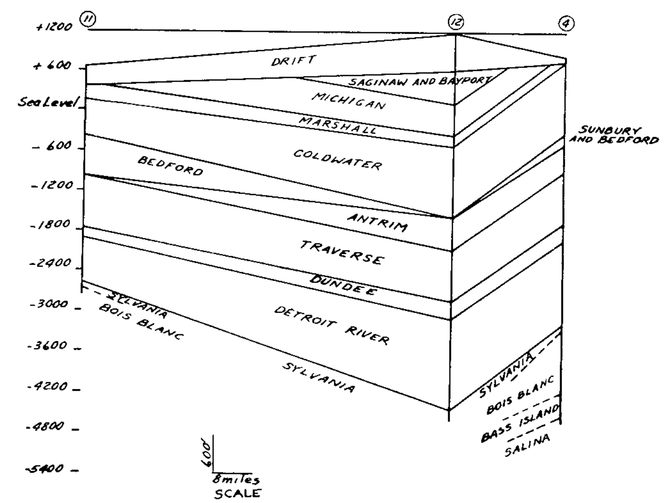


Fig. 8. *Continued.*

this breccia mass. Below 600 feet the rock is light colored Niagaran dolomite.

Wells drilled for water in the vicinity of Castle Rock and elsewhere in the southern part of the St. Ignace peninsula penetrated approximately 400 feet of green shale and "white stuff" according to drillers' reports. The "white stuff" is perhaps gypsum, but may be dolomite.

Better records of the subsurface Salina section are to be found in the Southern Peninsula, but not at the northern end. The northernmost deep well in the Southern Peninsula was drilled for salt by the McArthur brothers in Cheboygan in 1899-1901. Some samples are available from this well, but intervals in the section for which no samples exist, are of considerable magnitude. The log is also incomplete. Enough data are available, however, to make it obvious that this well is situated in the zone of collapse. The log reports "brecciated dolomites with slit cavities" and caved down to 750 feet. Probably the Salina formation is about 700 feet thick, extending from a depth of 850 to 1550 feet, to the top of the Niagaran dolomite. The samples are missing from 700 to 1300 feet, and from 1300 to 1360 feet, but a single sample of red and green shale is available. The samples from 1362 to 1550 are dolomite. The well log reports salt at 1400 feet, but no salt was in the samples.

The next well to the south that penetrated the Salina formation is the Presque Isle Development Company Chandler (Onaway) well in sec. 5, T. 34 N., R. 2 E., Presque Isle County. The surface elevation at this point is 830 feet. Samples from the Chandler well are incomplete, but a graphic log, probably prepared by H. H. Hindshaw, was given the writers by the Michigan Limestone and Chemical Company. According to the records the Salina formation is 1175 feet thick in this well, extending from a depth of 1625 feet to 2800 feet. The beds are undisturbed, showing that the well is outside the area of collapse. About 830 feet of the total Salina thickness is salt. The salt is in several beds of which the thickest, at the base of the salt series, is 225 feet, and the next thickest is a 145-foot bed lying at the top of the formation. The intervening beds are red and grey shales in the upper half of the section and dolomites and anhydrites in the lower half.

Also in Presque Isle County is the Alpena Land Company well No. 1, Lot 1, sec. 8, T. 33 N., R. 8 E. (Grand Lake well). The surface elevation of this well is about 608 feet. The well did not go to the Niagaran but stopped in "dolomite and anhydrite" beds of the Salina group at a total depth of 1712 feet, about 428 feet below the top of the Salina. Of the 428 feet of Salina penetrated about 275 feet is salt, the rest is practically all dolomite and anhydrite. From the mixed character of the samples it is evident that collapsing extended down to a depth of 1360 feet. This well is near the rim of the basin where collapse should be expected. Comparing the Grand Lake well with the Onaway well one finds that the upper salt and shale zone of the Onaway well is largely missing in the Grand Lake well. This zone, 450 feet thick in the Onaway well and containing 320 feet of salt, is represented in the Grand Lake well by 70 feet of mixed rock, mostly dolomite with a little salt. Leaching of 300 feet of salt in the uppermost part of the Salina formation in the Grand Lake area produced the collapse which is evident in the brecciated samples.

A stratigraphically deep test well on the west side of the Southern Peninsula in Antrim County is the Ohio-Chamberlain No. 1, sec. 14, T. 31 N., R. 8 W. This well was drilled by rotary. The Salina section lying between depths of 2750 and 4605 feet, is 1855 feet thick, and has about 430 feet of salt. The basal part of the Salina section is a brown dolomite about 125 feet thick. Above the dolomite is a 1400-foot section which contains 8 beds of salt, of which the thickest bed (160 feet) is immediately above the basal dolomite. Between the salt beds are beds of red and green shale and dolomite. Shale predominates in the upper half of the section and dolomite in the lower. Above the salt section to the top of the Salina formation is 320 feet of rock which consists predominantly of shale with some beds of brown dolomite.

Southwest of the Chamberlain well is the Copeland and Barton, Overby No. 1 well in sec. 5, T. 29 N., R. 12 W., Leelanau County. This is also a rotary well and the samples contain no salt, but about 170 feet of salt is listed in the log. According to the log, 1217 feet of Salina is present, extending from a depth of 2878 feet to 4095 feet, with a 140-foot brown dolomite series at the base. This well is probably in the collapse zone because: the samples above the Salina are mixed to an even greater extent than samples from a rotary well are normally mixed; the salt at the top of the Salina is thin, and the well is near the rim of the basin.

The best record of the Salina formation in northern Michigan is found in the samples obtained from the C. W. Teater Nevins No. 1 well in sec. 18, T. 32 N., R. 16 E., Alpena County. This well was completed in 1936. The surface elevation is 803 feet. The rock strata drilled are undisturbed, therefore, the edge of the disturbed zone lies between this well and the Grand Lake well about 14 miles to the northeast. The Salina formation extends from a depth of 2035 feet to 4115 feet. Of this 2080-foot thickness, salt beds aggregate about 1200 feet. Above the highest salt bed is 97 feet of grey, green and red shale and brown dolomite very similar in appearance to the shale and dolomite found at the surface on St. Ignace Peninsula and on Mackinac Island. Some subsurface stratigraphers extend the Bass Island group down to the top of the first Salina salt, but the correlation of this shale and dolomite series with the surface rocks is good evidence of the Salina age of these rocks.

Below the lowest bed of salt in the Nevins well is a 165-foot section of grey limestone, which is perhaps the equivalent of the dolomite in the lower Salina which outcrops along Carp River, Mackinac County. Between the lower dolomite and upper shale and dolomite the salt is in a series of beds which are from a few inches to 300 feet in thickness. Thick beds of dolomite with a little anhydrite occupy the intervals between the salt beds in the lower part of the formation, but variegated shales are in the upper half. The shale beds are as much as 100 feet thick in the lower part of the upper section but are much thinner above.

The only complete record of the Salina group in the center of the state was obtained from the log of the Gulf Bateson No. 1 well drilled in sec. 2, T. 14 N., R. 4 E., Bay County. This well penetrated the Salina from 5384 to 8270 feet—a total thickness for the formation of 2886 feet with approximately 1600 feet of salt. Above the top salt is 96 feet of brown dolomite and green shale similar to the dolomite and shale in the Nevins well and in the outcrop area, but only 10 feet of dolomite and anhydrite is below the basal salt—much less than elsewhere in the northern part of the basin. The basal salt bed is the thickest in the series having a total thickness of 442 feet. Some ten beds of salt which in general, decrease in thickness upwards to the top of the series are higher in the section. In the upper half of the salt series the rocks between the salt beds are mainly greenish gray shale with anhydrite. In the lower half of the section brown dolomite and anhydrite occupy the intervals between the salt beds.

SUMMARY. The Salina formation crops out in the St. Ignace peninsula but is at a depth of nearly 5400 feet in Bay County. The upper beds are variegated shales and thin brown dolomites that overlie the salt series in which as much as 1600 feet of salt is in a number of beds. The salt is thin along the northwest and northeast coasts of the Southern Peninsula where the upper beds have been leached and it is absent altogether in the Northern Peninsula where complete removal has taken place. Shales predominate between the salt beds in the upper part of the salt series, and dolomite beds predominate in the lower half. Nearly everywhere a basal dolomite section is below the lowest salt. The total thickness of the Salina (outside of the collapse zone) ranges from 1175 feet, in western Presque Isle County, to 2886 feet in Bay County.

BASS ISLAND FORMATION

The Bass Island strata are named from a group of islands near the western end of Lake Erie. The name has been applied to a series of dolomites cropping out in northern Ohio and Monroe County, Michigan. Subsurface stratigraphers applied the name to strata underground as drilling progressed from southeastern Michigan into the Michigan Basin. As now used the name is applied to a series of dolomitic beds lying above the Salina and below the Sylvania. The Bass Island at the surface in Michigan and Ohio is upper Silurian in age.

The subsurface Bass Island beds correlate with the St. Ignace formation. The Bass Island overlies the Salina formation everywhere beneath the surface in the Southern Peninsula. In different parts of this area it is variously overlain by Garden Island (?), Bois Blanc, Sylvania, and Detroit River rocks.

Near the southern tip of the St. Ignace peninsula test hole No. 13 of the Michigan State Highway Department was drilled during the course of an investigation to determine the feasibility of a bridge across the Straits of Mackinac. This well was drilled to a depth of 212 feet and, without doubt, went through the Bass Island (St. Ignace) formation and the uppermost Salina rocks. However, this area is one of excessive brecciation, and mixed with the Bass Island dolomite are samples of cherty limestones of Bois Blanc age, recognizable breccia, shale, and, in the lowest 40 feet of the well, gypsum fragments. This heterogeneous mixture of rock is almost valueless for geological correlation.

The same Southern Peninsula wells, excepting the Cheboygan well, discussed in the description of the Salina rocks supply data regarding the Bass Island strata. In addition, the Lobdell-Emery Myers No. 1 well in sec. 26, T. 35 N., R. 2 E., Presque Isle County, penetrated 108 feet of Bass Island sediments before being abandoned, and the Lupher Wilce Farm and Orchard No. 1 well in sec. 34, T. 28 N., R. 14 W., Leelanau County, penetrated the Bass Island and was bottomed in the salt section of the Salina group.

These records show that except in Bay County the thickness of the Bass Island is remarkably accordant. In Presque Isle, Antrim, Alpena and Leelanau Counties each of four wells logged from 325 to 348 feet of Bass Island rocks. In the Basin, in Bay County, the thickness is 574 feet. Apparently only the central part of the Michigan Basin sagged downward during Bass Island time. However, later sinking, mainly in Detroit River time, produced a wide variation in the elevation of the top of the Bass Island formation in northern Michigan. In the Chandler well in Presque Isle County the top of the Bass Island is 470 feet below sea level. Farther south, in Alpena County, it drops to nearly 900 feet below sea level and near the center of the Basin in Bay County to 4211 feet. On the west side of the state the top of the Bass Island is 1538 feet below sea level in Leelanau County and 1664 feet below sea level in Antrim County.

The top and base of the Bass Island group are invariably a light brown dolomite. The light brown to tan dolomite at the top of the formation is especially distinctive. Therefore, the top of the formation is easily identified, no matter which one of three or four different formations may lie above. Most of the section in the Bass Island formation between the top and bottom dolomites is also brown dolomite, but with greenish-grey dolomitic shales interbedded, especially in the lower half of the section. In fact, the lower half of the subsurface Bass Island section is very similar to the section exposed in the ferry mole cut near St. Ignace and probably correlates with it. The upper mass of dolomite probably correlates with the Hombach quarry rock in south St. Ignace. Some anhydrite is in the Bass Island section of the Chamberlain well in Antrim County, and is abundant in the Bateson well in Bay County. Apparently some dessication took place in the central part of the basin during Bass Island time. However, no salt beds have been found in the Bass Island, so evaporation did not proceed through the salt precipitation stage.

SUMMARY. The Bass Island strata of the subsurface correlate with the St. Ignace formation. They consist of light brown to tan dolomite, with greenish-grey dolomitic shales in the lower part of the section. Anhydrite is in the Bass Island rocks in the Michigan Basin.

The Bass Island section is about 335 feet thick in northern Michigan and 574 feet thick in Bay County.

GARDEN ISLAND FORMATION

The Garden Island formation, consisting of sandy dolomite with an Oriskany fauna, is the oldest Devonian formation in the outcrop

area. If present in the subsurface it should overlie the Bass Island dolomite series. A careful study was made of all available northern Michigan well samples from this part of the section. In the Onaway well and the Lobdell-Emery Myers No. 1 well in western Presque Isle County, sediments that may possibly correlate with the Garden Island formation were found. The samples of the Onaway well in sec. 5, T. 34 N., R. 2 E., are incomplete, but the log refers to a "hard white sandy limestone" between depths of 1250 and 1300 feet. This 50-foot section lies immediately above the Bass Island and immediately below the Bois Blanc formation, therefore, seems to correlate with the Garden Island.

Samples from this section in the Myers well, in sec. 26, T. 35 N., R. 2 E., are complete. A brownish limestone with a few sand grains lies between depths of 1235 and 1284 feet. This 49-foot limestone also lies immediately above typical light tan Bass Island dolomite and below a typical cherty Bois Blanc dolomite. The limestone is lithologically quite distinct from the overlying and underlying formations. It is also different from the Oriskany equivalent at the outcrop, the Garden Island formation, in that it is a limestone rather than a dolomite, but it is well known that the carbonate rocks in this part of the section change laterally from limestone to dolomite.

Of the several hundreds of wells examined only these two wells in Presque Isle County show any Garden Island sediments. It is probable that these sediments were once much more extensive, but that pre-Bois Blanc erosion removed all of them west of the Ontario peninsula excepting some residual patches here and there as in Presque Isle County and in the Beaver Islands.

BOIS BLANC FORMATION

The Bois Blanc formation, containing lower Onondaga fossils of lower Middle Devonian age, overlies the Bass Island rocks everywhere in northern Michigan except in the small area where the Garden Island formation is present. It crops out in the Mackinac Straits area, especially on the northern tip of the Southern Peninsula and on Bois Blanc Island. An isopach map of the formation shows that it thins to the south in southeastern Michigan, and disappears from the section only a few miles north of the point where the overlying and underlying formations crop out at the surface. To the east, however, it maintains its thickness and no doubt is continuous with the Onondaga formation on the Ontario Peninsula.

The Bois Blanc rocks have not heretofore been recognized as a separate formation in the subsurface section of Michigan. These strata have heretofore been included in either the Sylvania or Bass Island formations. As at the surface the subsurface Bois Blanc formation is characterized by a large amount of chert and abundant fossils.

The subsurface section has the same three-fold division of the Bois Blanc formation in northeastern Michigan as the formation at the outcrop. For example, in the Chandler (Onaway) well in sec. 5, T. 34 N., R. 2 E., Presque Isle County, and in the Nevins well, in sec. 18, T. 32 N., R. 6 E., Alpena County, the basal part of the Bois Blanc section consists of from 100 to 150 feet of chert and dolomite. The middle part is 130 to 150 feet of cherty limestone, and the top part of the formation is non-cherty limestone which cannot be distinguished from the basal Detroit River limestone. The absence of a recognizable contact between the Detroit River and Bois Blanc will be discussed later in the description of the Detroit River group.

The lithology changes to the south, and in the Yeo No. 1 well in sec. 2, T. 21 N., R. 2 E., Ogemaw County, the entire Bois Blanc section is cherty limestone and limestone, with no cherty dolomite. In the Yeo well the Bois Blanc formation is thicker than in any other place so far drilled, as it is nearly 1000 feet from the top of the Bass Island to the base of the Sylvania. Most of this thick section is cherty limestone, but about 110 feet of non-cherty limestone lies at the top of the formation.

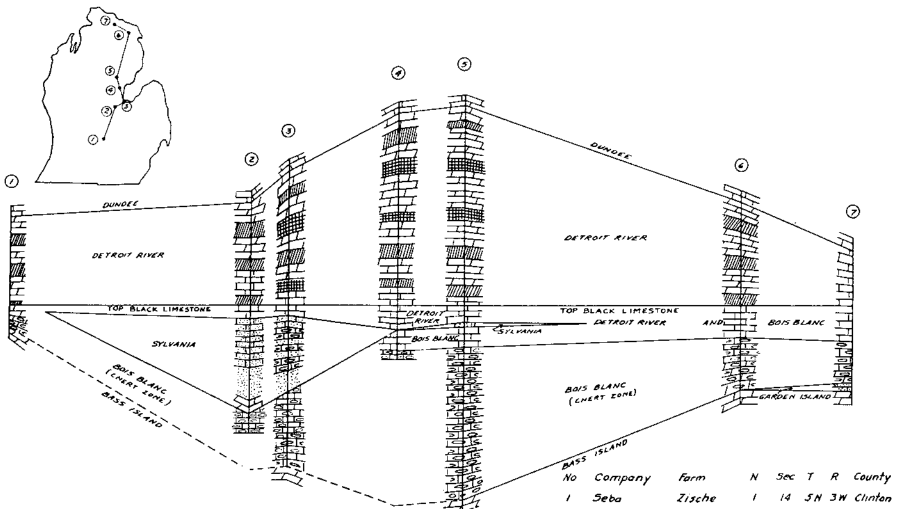
On the western side of the state a greater variation exists in Bois Blanc lithology. The Chamberlain well in sec. 14, T. 31 N., R. 8 W., Antrim County, is similar to the Ogemaw well. No cherty dolomite is at the base of the section in either well. The top limestone member and the middle cherty limestone member are present, however. Farther to the southwest, in Leelanau and Manistee counties no limestone is in the Bois Blanc section. The upper 70 to 100 feet is non-cherty dolomite and below that and down to the top of the Bass Island is cherty dolomite. The dolomite is about 260 feet thick in the Wilce Farm and Orchard well in sec. 34, T. 28 N., R. 14 W., Leelanau County, but is only about 60 feet thick in the Ruggles and Rademaker well No. 24, sec. 12, T. 21 N., R. 17 W., Manistee County.

The overlying Sylvania formation is entrenched in the Bois Blanc. Pre-Sylvania erosion carved a wide trough in the upper Bois Blanc rocks across central and southeastern Michigan, and subsequently this trough was filled with sandy sediment. The accompanying columnar section (fig. 7) illustrates the entrenchment of the Sylvania sandstone formation into the Bois Blanc formation in

Midland and Bay counties. The limestone in the upper part of the Bois Blanc formation, which is present everywhere north of Arenac County, is completely cut out and the base of the Sylvania overlies the cherty section of the Bois Blanc. In the non-Sylvania wells on the north flank of the Basin 130 to 190 feet of limestone above the chert section undoubtedly belongs to the Bois Blanc formation. This limestone section was removed by pre-Sylvania erosion in the central part of the Southern Peninsula. In fact, the 540-foot Sylvania section in Midland County was deposited in the trough from which not only the upper Bois Blanc limestone but also some 350 feet of the upper part of the chert section was removed. Only about 25 feet of Sylvania and below that only 110 feet of Bois Blanc limestone are in the Yeo No. 1 well in sec. 2, T. 21 N., R. 2 E., Ogemaw County. If the Sylvania occupied space formerly taken up by Bois Blanc formation that leaves a limestone section of only 135 feet, which is less than the thickness of the section in Alpena and Presque Isle counties where the original thickness of the upper Bois Blanc limestone was probably about 200 feet. In the pre-Sylvania erosion interval about 90 feet of this limestone was removed and then 25 feet of Sylvania was deposited on the erosion surface.

The top of the Bois Blanc formation ranges in elevation from about 600 feet above sea level at the outcrop area to 4,575 feet below sea level in the Fee No. M-2 well in sec. 27, T. 14 N., R. 2 E., Midland County. The Thompson No. 1 well in sec. 3, T. 20 N., R. 3 W., Clare County, did not reach the top of the Bois Blanc formation at 4,735 feet below sea level, where the hole was abandoned. Of course, in the central part of the basin the top of the Bois Blanc formation is actually several hundred feet below the original top due to removal by erosion. The thickness of the Bois Blanc formation ranges from a minimum of 165 feet in the Manistee County well to 1,000 feet in Ogemaw County. In the southern part of the state the Bois Blanc formation thins and eventually disappears completely near the Ohio line.

SUMMARY. In northeastern Michigan the Bois Blanc formation has the three-fold division found at the outcrop. In western Michigan the limestone parts of the section have been replaced by dolomite. In central Michigan the upper part of the Bois Blanc formation has been removed by pre-Sylvania erosion and Sylvania deposited in a part of the space formerly occupied by the cherty and higher limestones of the Bois Blanc formation.



No	Company	Farm	N	Sec	T	R	County
1	Seba	Zische	1	14	5N	3W	Clinton
2	Dow	Fee	M2	27	14N	2E	Midland
3	Gulf	Bateson	1	2	14N	4E	Bay
4	Major	McTaggert	1	26	19N	3E	Arenac
5	Pure	Leo	1	2	21N	2E	Ogemaw
6	Teator	Nevins	1	18	32N	6E	Alpena
7	Presque Isle Dev. Co	Chandler	1	5	34N	2E	Presque Isle

Fig. 9. Cross section of northeastern part of the Southern Peninsula of Michigan. Datum top of black limestone near base of Detroit River formation. Showing intrenchment of Sylvania formation in Bois Blanc.

The structural relief of the Bois Blanc erosion surface is about 5200 feet. The formation ranges in thickness in northern Michigan from 165 to 1000 feet.

SYLVANIA FORMATION

The Sylvania formation crops out in the southeastern corner of Michigan but does not crop out in northern Michigan. It thins and disappears north of a line drawn from Saginaw Bay to Grand Traverse Bay. The Sylvania formation occupies a trough which crosses central Michigan from the Lake Michigan shore to Saginaw Bay and then curves southward to the outcrop area in Monroe County. The formation consists of sandstone, sandy dolomite, and sandy limestone. Where both limestone and dolomite are present the limestone is usually in the upper half of the formation and the dolomite is in the lower half. The sandstone is in discontinuous lenses. From one to six sandstone beds may be penetrated in wells, and the individual beds vary from a few inches to nearly 200 feet in thickness.

The thickest Sylvania section drilled up to 1944 is in the Fee No. 2 well in sec. 27, T. 14 N., R. 2 E., Midland County. In this well the Sylvania extends from a depth slightly below 4600 to nearly 5150 feet—a total thickness of about 540 feet. The upper half of this section is sandy limestone; which is underlain by 190 feet of sandstone, and nearly 90 feet of sandy dolomite is at the base. In the Bateson well in Bay County the Sylvania section is 455 feet thick. At the base is a 100-foot sandstone and above are five more sandstone beds with sandy or cherty limestone lying between the sandstone beds. It is possible that some of the chert found in the Sylvania formation in the Michigan Basin came from the Bois Blanc formation which was exposed and subject to erosion on the north flank of the Sylvania trough when the Sylvania formation was being deposited.

The Thompson No. 1 well in sec. 3, T. 20 N., R. 3 W., Clare County, is bottomed in the Sylvania formation 310 feet below the top of the formation which lies at a depth slightly below 5,620 feet. The lowest 20 feet of section drilled in this well is cherty dolomite, which may possibly belong to the Bois Blanc formation.

North of the Clare-Midland-Bay county area the Sylvania formation is absent. It is not in the McTaggart well in sec. 26, T. 19 N., R. 3 E., Arenac County. About 25 feet of sandy dolomite constitutes the Sylvania section in the Yeo well in sec. 2, T. 21 N., R. 2 E., Ogemaw County. Farther to the north the Sylvania is absent.

On the west side of the state logs and samples from the wells from Cheboygan to Antrim County showed no Sylvania, but the formation is present from Leelanau to Mason counties. The Wilce well in sec. 34, T. 28 N., R. 14 W., Leelanau County, drilled through 18 feet of sand between 2,120 and 2,140 feet. Lower Detroit River dolomite is above the sand and upper Bois Blanc dolomite is below it. The Ruggles and Rademaker well No. 24 in sec. 12, T. 21 N., R. 17 W., Manistee County, found only good sand about 52 feet thick in the Sylvania formation. The Campbell No. 1 well in sec. 16, T. 17 N., R. 15 W., Mason County, had about 20 feet of dolomitic sand underlain by 20 feet of good sand in the Sylvania.

SUMMARY. Sandstone, sandy dolomite, and sandy limestone of the Sylvania formation, occupy a trough carved out of older rocks in central and southeastern Michigan. The formation is absent in northern Michigan. The sandstone beds are large lenses. Chert, perhaps derived from the Bois Blanc, is in some wells. The total thickness of the Sylvania ranges from a few feet to 540 feet.

DETROIT RIVER GROUP[1]

The type locality of the Detroit River is in southeastern Michigan along the Detroit River where exposures gave the group its name. The Detroit River group extends northward across the Michigan Basin but is very poorly exposed in the Mackinac Straits area. One exposure of limestone, probably basal Detroit River in age, southwest of Mackinaw City, is described in the section on surface stratigraphy. Between this outcrop and the approximate latitude of Cheboygan the Detroit River rocks no doubt underlie the glacial drift over a wide belt, but the drift is very thick and no exposures are known. The beach shingle on North Fox Island contains a black argillaceous dolomite which may correlate with the black limestone or dolomite found in well samples in northern Michigan. Also the pale buff dolomite found on the beach on Isle Le Galet probably came from lower Detroit River outcrops. The Detroit River formation is Middle Devonian in age.

In northern Michigan the Detroit River rocks are underlain by the Bois Blanc formation and in central Michigan by the Sylvania sandstone formation. Where the Sylvania is present the base of the Detroit River can be determined but in most areas where the Detroit River directly overlies the Bois Blanc it is impossible to determine the boundary between the two. The Bois Blanc deposition closed with limestone and the Detroit River phase started with limestone deposition. No color changes, sand grains, detrital zones, or other evidences of an unconformity have been found in the section. However, the lower Detroit River does contain a marker which can be used in correlation and the top of which was used as a datum plane in making the cross section (fig. 9) used to illustrate the entrenchment of the Sylvania into the Bois Blanc. This marker bed is a dark brown to black limestone, except in Mason, Manistee, and Leelanau counties, where it is a dolomite. The top of the black bed makes a distinct reference point, but in many places the lower boundary is indistinct due to a gradual lightening of color. The top of the black limestone is from 50 to 90 feet above the Sylvania (where present) in the eastern part of the Michigan Basin, and from 20 to 60 feet above in the western part of the Basin. Because the black limestone is above the Sylvania sandstone, it must belong in the Detroit River formation and, therefore, does not mark the boundary between the Detroit River and Bois Blanc formations. However, where the Sylvania sandstone is

[1]Exclusive of the Sylvania, which is classified as lower Detroit River by some writers.

absent the limestone does give a clue as to the approximate boundary between the two formations.

The lithology of the Detroit River formation is most variable. Around the rim of the basin, in wells in the northern part of the Southern Peninsula and in the outcrop area along the Detroit River, the formation consists of massive limestones and dolomites. Out in the Basin the formation increases greatly in thickness and contains thick evaporite deposits of rock salt, gypsum or anhydrite. However, the basal part of the formation is invariably carbonate rock containing no evaporites. It is limestone except in the western edge of central Michigan where it is dolomite. This basal zone of carbonate rock includes the black limestone which nearly everywhere is from 50 to 100 feet below the top.

The evaporite series is above the basal carbonate rock zone everywhere except on the north rim of the basin. In the Chandler (Onaway) well in sec. 5, T. 34 N., R. 2 E., Presque Isle County, the entire Detroit River section is limestone. However, farther south, the Nevins well in sec. 18, T. 32 N., R. 6 E., in Alpena County, penetrated nearly 600 feet of alternating dolomite and anhydrite between the base of the Dundee and the top of the basal limestone zone. Still farther south in the Yeo well in sec. 2, T. 21 N., R. 2 E., Ogemaw County, the evaporite series is 1,145 feet thick—the greatest thickness yet found in wells drilled in the Southern Peninsula. In the Yeo well salt is also found in the section. Wells drilled in Arenac, Bay, and Midland counties have a similar but thinner section of dolomite, salt and anhydrite. The Fee No. M-2 well in sec. 27, T. 14 N., R. 2 E., Midland County, however, has limestone instead of dolomite in the lower half of the evaporite section.

The evaporite section, including salt, is 600 to 700 feet thick on the west side of the Basin in Leelanau, Manistee, and Mason counties. Figures 10, 11, 12, 13[2] show the aggregate thickness of the Detroit River salt, and the regional structure of the Dundee-Detroit River contact.

The structural relief on the base of the Detroit River formation is considerable. Between the outcrop area of northern Michigan, where the elevation of the basal Detroit River is over 600 feet above sea level, to the Thompson well in sec. 3, T. 20 N., R. 3 W., Clare County, this stratigraphic boundary drops over 5,000 feet to a below sea level elevation of –4430. Because of the basinward thickening

[2]Prepared by Marie Tharp and submitted in partial fulfillment of the requirements for degree of Master of Science in the University of Michigan, 1944.

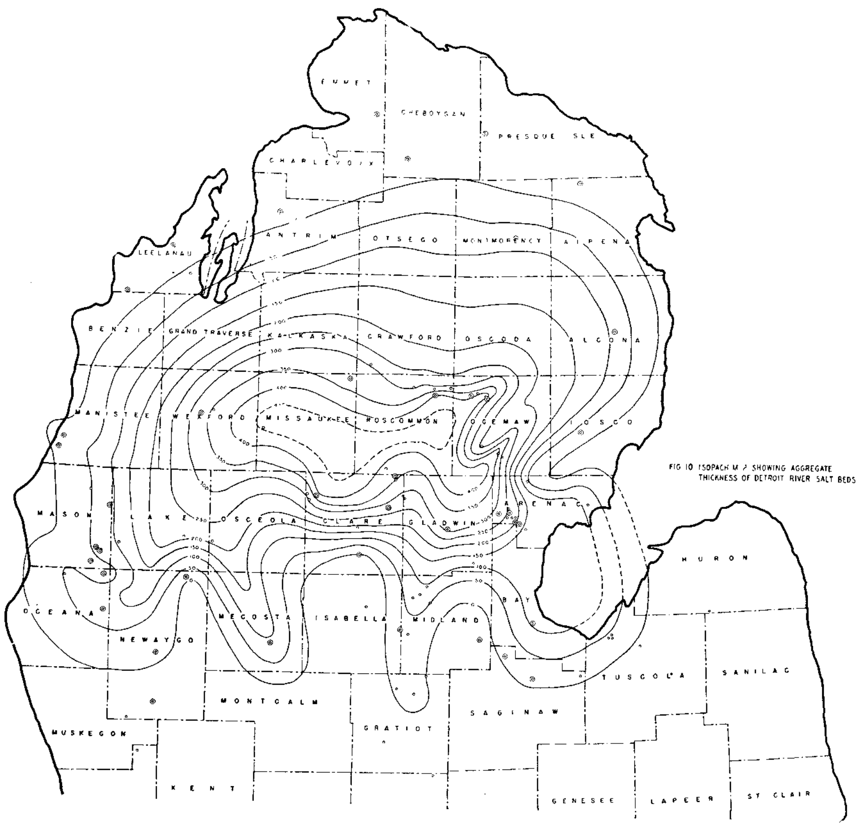


Fig. 10. Isopach map showing aggregate thickness of Detroit River salt.

of the Detroit River section, the structural relief of the top of the formation is much less (fig. 13).

Obviously the first sea that spread over the Southern Peninsula of Michigan in early Detroit River time was a normal lime depositing sea. During this time the sediments that became the basal limestone were deposited throughout the area. Subsequently the limestone became dolomitized on the western side of the peninsula. The basin began to sink during this early period, as shown by the greater thickness, 190 feet, of limestone below the black bed in Clare County which is much thicker there than elsewhere. With the forming of a topographic basin evaporation began and dolomite and anhydrite were deposited everywhere except near the rim. There limestone continued to be deposited where inflow of fresh water prevented precipitation of calcium sulphate, (the log of the Chandler well in Presque Isle County supports this contention).

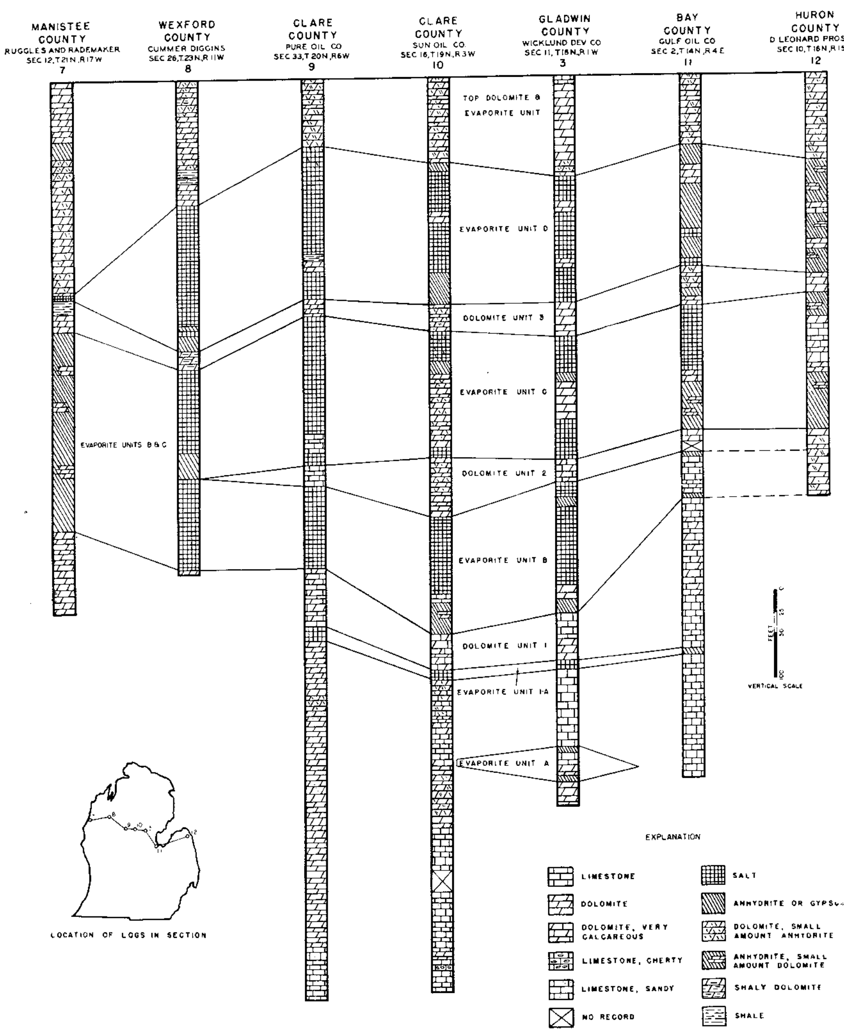


FIG. 11. WEST-EAST SECTION SHOWING LITHOLOGY AND THICKNESS OF THE DETROIT RIVER SERIES FROM MANISTEE COUNTY TO HURON COUNTY.

Fig. 11. West-East section showing lithology end thickness of the Detroit River series from Manistee County to Huron County.

Because evaporites are along the Lake Michigan shore in Mason and Manistee counties it can be assumed either that no fresh water flowed into that part of the basin or that the basin rim was farther west in Detroit River time in the area now submerged by the lake.

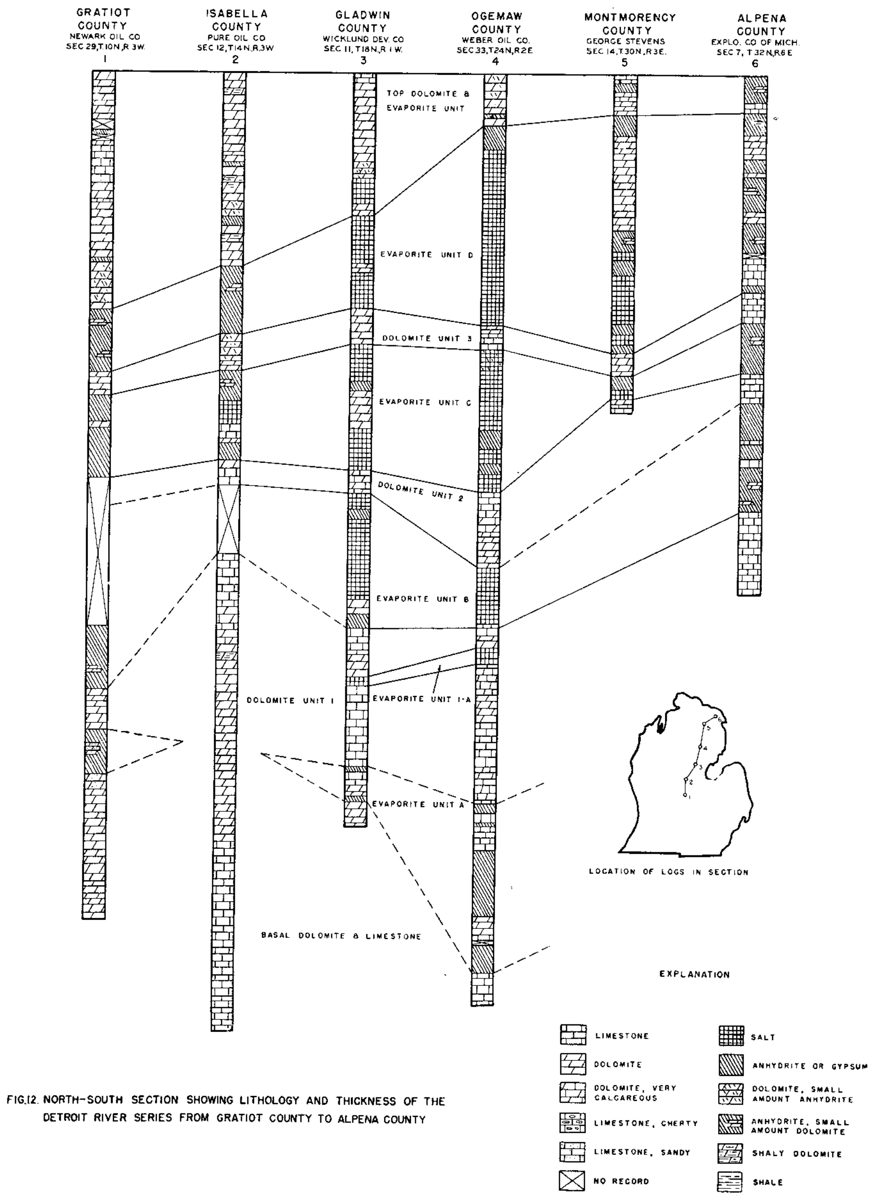


Fig. 12. North-South section showing lithology and thickness of the Detroit River series from Gratiot County to Alpena County.

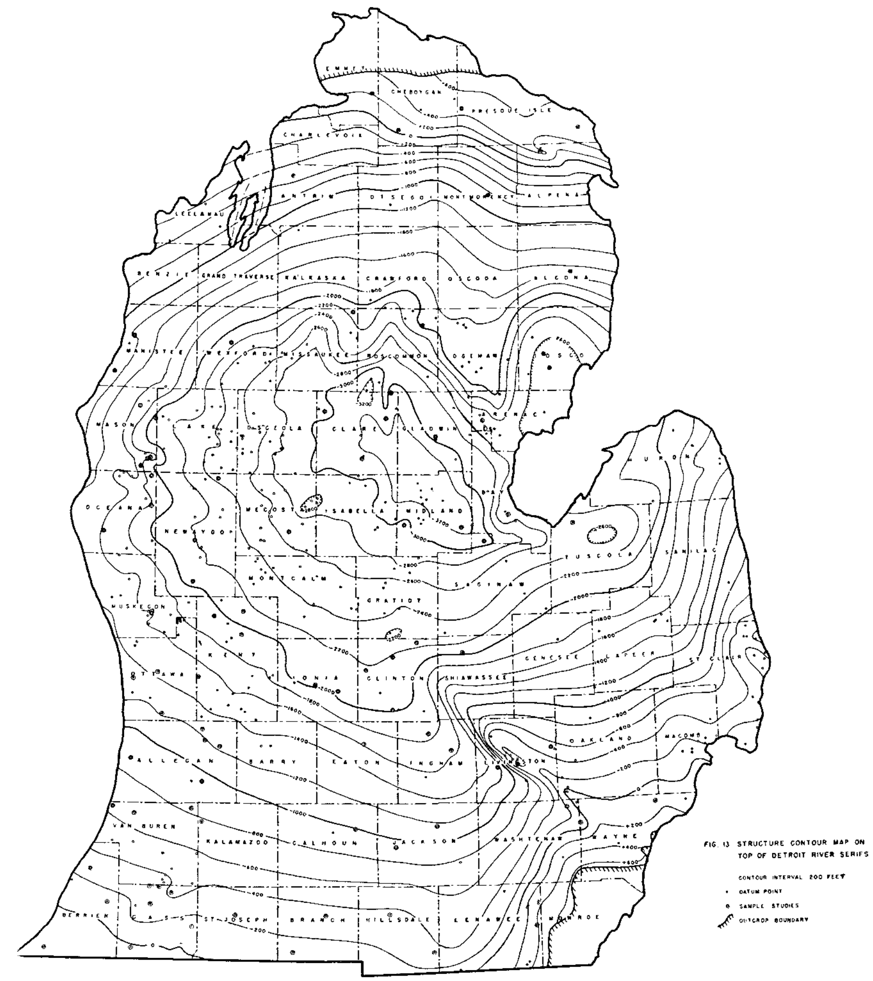


Fig. 13. Structure contour map on top of the Detroit River series.

During the latter half of Detroit River time the sea had shrunk so that it covered only the central part of the Detroit River basin and in this smaller sea salt was precipitated, wth anhydrite and dolomite. A possible source for this salt was discussed in the section on the Mackinac breccia.

SUMMARY. Comparison of the subsurface Detroit River beds with beds at the surface is prevented by the almost complete absence of outcrops of this formation in the Straits of Mackinac area.

Well samples show that the basal rocks of the Detroit River formation is a limestone (or dolomite) which is difficult to distinguish from the upper Bois Blanc limestone where the Sylvania formation is absent. From 20 to 90 feet above the base of the Detroit River is a black limestone which can be used as a marker bed.

Above the basal Detroit River limestone in the Michigan Basin is an evaporite series containing dolomite, anhydrite, and salt. This series is absent on the rim of the Basin.

The average thickness of the lower Detroit River limestone (or dolomite) series is 130 feet. The evaporite series ranges in thickness from about 600 feet, on the flanks of the Basin, to 1,145 feet near the center of the Basin.

Between the outcrop area south of Mackinaw City and Clare County, the base of the Detroit River drops over 5,000 feet in elevation.

The lower Detroit River carbonate rocks are believed to have been deposited on the floor of a marine embayment, whereas the evaporite series was deposited in an enclosed and shrinking continental sea.

REGIONAL STRUCTURE

The Mackinac Straits area is on the north flank of the Michigan Basin. Therefore, the regional strike is approximately east-west, and the direction of dip is south. The degree of dip increases with stratigraphic depth, as shown by the following table:

Average dip per mile between outcrop and the Bateson Well (Bay County)

Upper Surface, Detroit River group	22
Upper Surface, Bois Blanc formation	30
Upper Surface, Bass Island group	30
Upper Surface, Salina group	34
Upper Surface, Niagaran series	48

The increase in dip with stratigraphic depth is most marked within the Detroit River group (8 feet per mile difference) and the Salina group where the difference between top and bottom dips is 14 feet per mile. The reason for this increase in dip is that sinking took place in the Michigan Basin while the Detroit River and Salina sediments were being deposited. Consequently these formations thicken basinward, and the dips on the upper surfaces (which initially were flat or nearly so) are appreciably less than the dips on the lower contacts. Moderate sinking of the Michigan Basin also took place in Bass Island time. These conclusions, based on regional dip figures, are verified by the type of sediment deposited in the

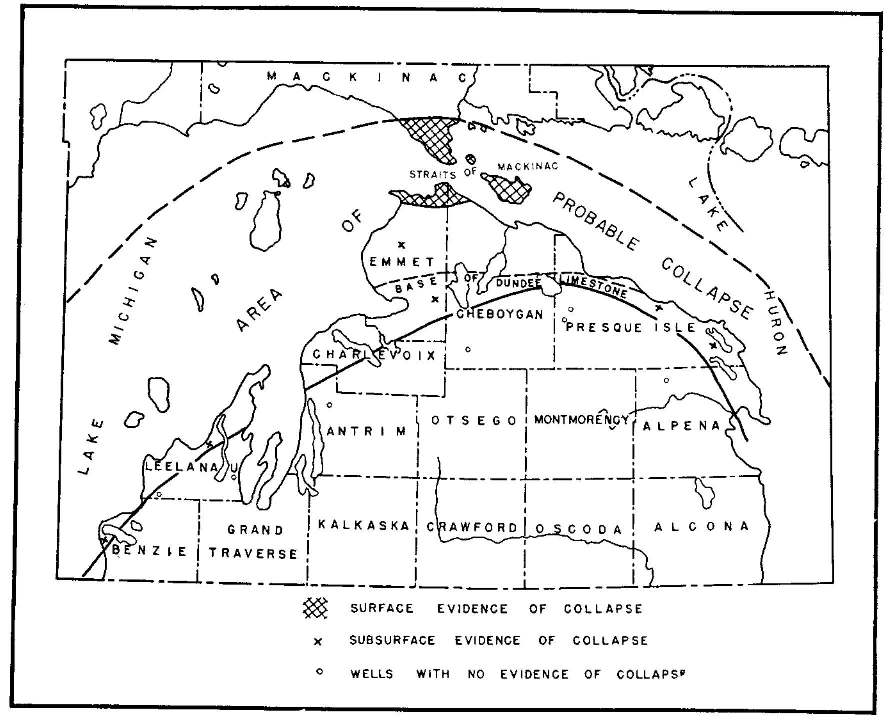


Fig. 14. Map of Mackinac Straits areas showing zone of collapse and exposures of Mackinac Breccia.

Basins. During the period of greatest sagging, the Salina, thick beds of salt with some anhydrite were deposited. Thinner beds of salt and considerable anhydrite were precipitated during Detroit River time. Anhydrite only, and in relatively minor amounts, was deposited during Bass Island time.

The dip per mile figures given in the tabulation are relative. They are based on the log of the Bateson well which is not at the very bottom of the Basin. Therefore, the actual dips are somewhat greater. Furthermore, the figures are for the *average* dip between the outcrop and the Bateson well—the degree of dip decreases progressively basinward from the rim to the central part of the Basin where the dips are slight. Therefore, high on the flanks of the Basin (as in the Straits area), the dips are greater than the average. The regional dip of the rocks in the vicinity of Mackinac Straits is from 50 to 65 feet per mile.

All exposures in the Straits area are in the zone of collapse (fig. 14). Structure maps of the area can be of little value as they depict the structure of the collapsed material only and not the structure of the underlying Niagaran and older rocks. On such maps, the many faults which bound the megabreccia blocks are the most prominent features. Also because of the relatively steep dips of the megabreccia, structure maps made on them show local structural features of unusual magnitude. The writers do not believe it possible to find any clues as to the character of the local structure from surface observations in the zone of collapse.

In all probability, reversals of dip do occur in the rock strata of northern Michigan, and on St. Ignace peninsula. Where the collapse zone reaches the surface reversals can be determined only by structure drilling through the collapsed rock to the top of the Niagaran beds. Where Dundee and younger rocks overlie the collapsed materials it is probable that any late Paleozoic folding that took place created comparable structural features in both the older and younger rocks. In other words, an anticline in the Traverse beds would be underlain by an anticline in the Niagaran rocks, although several hundred feet of massive breccia might be between them. However, differential compaction and settling of the younger rocks overlying the breccia erosion surface may have produced folds that are entirely confined to the Dundee and higher beds.

Chapter V

Economic Geology

OIL AND GAS POSSIBILITIES

The oil and gas possibilities in the block of 15 counties lying north of T. 24 N., in the Southern Peninsula, and in Mackinac and southern Chippewa counties in the Northern Peninsula are discussed in this section. Greatest emphasis is placed on the possibilities for oil and gas in the lower Devonian and upper Silurian rocks because this part of the section was studied in the field. However, important evidence show possibilities of commercial production in younger rocks in central northern Michigan, and the older rocks throughout the area cannot be ignored as potential sources of oil and gas.

The commercial production nearest the area is in three fields which are immediately south in T. 24 N. The oldest of these fields is Richfield, in northeastern Roscommon County, T 24 N., R. 1 W. It was discovered in December, 1941, and by January 1, 1945, had 15 producing wells and a total production of 214,976 barrels. The pay zone is in, and about 1,000 feet below the top of the Detroit River group, at a depth of 4,185 feet. The pay has been named the "Richfield." Subsequent to its discovery the same zone was found to be productive in a half dozen newer fields.

The second field discovered in T. 24 N., is the East Norwich in northeastern Missaukee County, T. 24 N., R. 5 W. The discovery well was completed at a depth of 4,524 feet in the Richfield zone on July 23, 1942. The third well drilled in the East Norwich field found commercial production in the Dundee at a depth of 3,096 feet. One well in the field was producing from the Traverse in January 1945. Top of the Traverse formation is at 2,375 feet. The field produced 211,976 barrels of oil from 19 wells by January 1, 1945. In October 1942 the first successful well was drilled on the large Rose City anticline in northwestern Ogemaw County. Oil in this well is from the Richfield zone at a depth of 4,287 feet. Total production from 5 wells in the Rose City field was 31,152 barrels by the close of 1944 from one Traverse and four Detroit River wells.

One oil strike has been made, in Montmorency County, where seepages of Antrim shale gas through the glacial drift have caused sporadic interest in the area for many years. An unsuccessful Detroit River test, the Austin Rea No. 1, in sec. 24, T. 30 N., R. 3 E., was drilled in 1941 to a depth of 2,187 feet. It penetrated about 500 feet of Detroit River beds, but logged only a "smell of oil" 407 feet below the top. The second Detroit River test drilled in this county,—the Crank No. 1 well in sec. 15, T. 30 N., R. 3 E.,—struck oil 375 feet below the top of the formation, immediately beneath a salt bed. The well was drilled in the spring of 1944 to a depth of about 2,270 feet. The oil zone is between 2,180 and 2,186 feet. After drilling in, oil and water rose in the hole to the top of the casing and overflowed. Attempts to shut off the water were unsuccessful, but the well had not been abandoned by May, 1945. The possibility of producing oil in commercial quantities this far north in Michigan aroused considerable interest. Several tests have been started but no commercial wells had been drilled in by mid-1945.

More than 100 dry holes have been drilled in the 17 counties, but only 24 of these wells can be considered adequate tests. The others are either shallow wells (less than 1,000 feet deep) or were not drilled below the upper Detroit River beds. No wells have been drilled in Oscoda County for oil. Furthermore, many of these tests were drilled without benefit of geological advice, so are not necessarily tests of potential oil "traps." Obviously, the area has not been adequately explored.

POTENTIAL OIL AND GAS RESERVOIR ROCKS

PRE-TRENTON ROCKS: Only two wells in the northern Southern Peninsula of Michigan have penetrated rocks below the Trenton formation,—the Nevins well in Alpena County and the Chamberlain well in Antrim County. Three wells in the area in the Northern Peninsula drilled into Cambro-Ordovician beds. Two are in western Mackinac County: the Stack Lumber Company well in sec. 26, T. 44 N., R. 12 W., and the Hiawatha Club well in sec. 17, T. 44 N., R. 9 W.; the third is the Pickford well in sec. 6, T. 43 N., R. 1 E., southern Chippewa County. Because of the scanty data, it is difficult to map the distribution of the pre-Trenton rocks in Michigan, and geologists have not yet reached an agreement on the nomenclature that should be applied to this part of the stratigraphic section.

No oil or gas has been found in pre-Trenton rocks in Michigan, but they are very important reservoir formations in the Mid-Continent oil district, and shows of oil have been recorded from them

in the Illinois Basin and along the Cincinnati Arch in Indiana and southwestern Ontario. Lithologically the pre-Trenton beds in Michigan consist of thick sandstones and siliceous dolomites, not dissimilar to the lithology of the pre-Trenton in the Mid-Continent oil fields. Also the Michigan beds are sufficiently porous and permeable to permit oil accumulation. They yield large quantities of water wherever penetrated by the drill, and the porosity is also evident in the area of outcrop. We know of no geological reason why a suitable "trap" in pre-Trenton rocks in the area should not contain oil. The depth to these formations varies from 800 feet in southern Chippewa County to between 9,000 and 10,000 feet in southern Crawford County.

TRENTON-BLACK RIVER BEDS: The Trenton group has produced a large quantity of oil in the Lima-Indiana district south of the southern border of Michigan. It is also the oil reservoir in the Deerfield pool in western Monroe County, Michigan. Oil or gas (or both) are produced from Trenton rocks in several fields in Ontario, and on Manitoulin Island a few hundred barrels of oil have been obtained from the upper 20 feet of the Trenton limestone.[1]

The Trenton-Black River beds were penetrated by five wells which were bottomed in pre-Trenton rocks. In the Hiawatha Club well in Mackinac County an oil show was recorded 150 feet below the top of the Trenton, and shows of oil are reported in the Kreetan well in sec. 17, T. 41 N., R. 7 E., Chippewa County (Drummond Island), 19 and 35 feet below the top of the Trenton. Apparently, worthwhile production in the Trenton formation is confined to areas where dolomitization of the limestone increased the porosity. The majority of the test wells reaching the Trenton formation in Michigan drilled into limestone. However, considerable dolomite is in the Trenton section in the Hiawatha Club well in Mackinac County, and some of these dolomite beds yield large quantities of water. Samples are not available from the Kreetan well on Drummond Island. The oil there may or may not be coming from a dolomitized limestone. In any event, the oil shows and evidence of porosity in the Trenton in the Northern Peninsula invite further exploration of this formation in the Straits area where it lies at estimated depths of 1,000 to 3,000 feet below sea level.[2]

[1]Hume, G. S., Oil and gas in eastern Canada: Canadian Geol. Survey, Econ. Geol. Series No. 9, 62-66, 1932.

[2]Cohee, Geo. V., Geology and oil and gas possibilities of the Trenton and Black River of the Michigan Basin. U. S. Geol. Survey, Oil and Gas Investigations, Prelim., ch. 11, 1945.

NIAGARAN SERIES: Rocks of Niagaran age produce gas and oil in Ontario, but neither gas nor oil has been found in commercial amounts in these rocks in Michigan. The Kreetan well on Drummond Island reported gas 46 feet below the top of the Manistique formation. Water was found in the Niagaran rocks in the Kreetan and Hiawatha Club wells. In the Straits and Les Cheneaux Islands areas several artesian wells have been drilled into the dolomites of the Niagaran. The principal aquifer lies from 65 to 100 feet below the top of the series. Obviously, Niagaran rocks in the Straits area have both porosity and permeability. How far south this condition continues is not known. The top of the Niagaran drops from a depth of about 600 feet at St. Ignace to an estimated 3,000 feet in central Cheboygan County. The Niagaran series of rocks also merits exploration in the northern part of the Southern Peninsula.

SALINA GROUP: The Salina shales, dolomites, and evaporites are at, or close to, the surface in the Straits region, but lie at depths below 5,000 feet near the center of the basin. Most of the rock layers have insufficient porosity for the storage of commercial quantities of oil or gas. However, some of the dolomites, especially in the lower part of the section, are porous. Gas and natural gasoline have been obtained from the Salina from wells drilled in Livingston and Washtenaw counties, and gas only from a St. Clair County well. Only one Salina test in central or northern Michigan had important shows of oil or gas, the Gulf Refining Company Bateson No. 1 in sec. 2, T. 14 N., R. 4 E., Bay County, which struck a strong flow of gas in a dolomite at a depth of 7,760 feet. This dolomite is immediately below a thick salt bed (the second salt bed above the base of the Salina) and is 2,280 feet below the top of the Salina. A second test well, drilled about a mile to the northwest, was unsuccessful. The lower Salina section on the north flank of the Michigan Basin contains dolomite beds, but no data are available concerning their porosity.

BASS ISLAND GROUP: The St. Ignace formation of the Bass Island group is exposed in the Straits area. It consists of dense massive dolomites, and shaly dolomites. The porosity is insufficient for the storage of fluids. This condition appears to continue down the flanks of the Basin, for the logs of wells in northern Michigan penetrating the Bass Island rocks not only report no oil or gas shows, but also report no water in these beds.

GARDEN ISLAND FORMATION: The basal Devonian Garden Island formation, the age equivalent to the Oriskany sandstone, consists at the outcrop of hard, dense dolomite and sandy dolomite rather than sandstone. That it has sufficient porosity for oil accumulation is questionable. Furthermore, the Garden Island formation is in northern Michigan only in scattered remnants on a pre-Bois Blanc erosion surface. Three wells have penetrated rocks that may prove to be the Garden Island formation. Two, in Presque Isle County, are discussed in the chapter on Subsurface Stratigraphy. The third, for which samples are not available, is the Lenoran Petroleum Company Commeau No. 1 well in sec. 23, T. 35 N., R. 1 E. The log of this well records 13 feet of "water sand" at a depth of 1,122 feet. The depth to the top of the Garden Island (?) formation in western Presque Isle County is about 1,250 feet. Possibility of finding oil and gas in the Garden Island formation is much lessened by the probable unequal, spotty porosity, erratic distribution, and the relatively shallow depth of the formation where it is present.

BOIS BLANC FORMATION: In the 17-county area, 18 wells have penetrated the Bois Blanc formation. Logs of these report no oil or gas shows, but strong flows of water were logged in the lower cherty part of the section, in several wells. For example, in two wells in Leelanau County, the Wilce Farm and Orchard well in sec. 34, T. 28 N., R. 14 W., and the Heimforth well in sec. 6, T. 28 N., R. 11 W., water was found in cherty dolomite at from 205 to 235 feet below the top of the Bois Blanc. In the Nevins well in Alpena County, and the Chandler (Onaway) well in Presque Isle County, water was found in the Bois Blanc chert.

The top of the Bois Blanc chert section drops from an elevation above lake level on Mackinac Island to depths of 1,600 feet in southern Cheboygan County and below 4,000 feet in southern Ogemaw County. Sheet porosity is more likely to be found in the Bois Blanc formation, with its water-bearing chert section, than in the other beds above the pre-Trenton rocks in the area. It should be tested in all future wells exploring structural "traps" in northern Michigan.

SYLVANIA FORMATION: The Sylvania sandstone and dolomite formation does not outcrop in northern Michigan. In fact it is not beneath most of the area under discussion. The northern boundary of the formation crosses Crawford, Kalkaska, northern Grand Traverse, and southern Leelanau counties. Only one well north of T. 24 N. penetrated the Sylvania formation,—the Wilce Farm and Orchard well in Leelanau County, which penetrated 18 feet of water-bearing sand at a depth of 2,124 feet. To date tests of the Sylvania formation in Michigan have been disappointing. The Bateson well in Bay County found five feet of oil-saturated sand between 3,960 and 3,965 feet (15 feet below the top of the formation) and it is possible that a Sylvania oil pool of small size lies beneath the surface in the vicinity. The Sylvania sandstones apparently are large lenses, not sheets of sands. But these sandstone bodies are high in porosity and permeability, and many no doubt are of sufficient size to store a large volume of oil. A likely area for further prospecting is in the southwest part of the 17-county area, where the Sylvania formation wedges out to the north on the northwest flank of the Michigan Basin. Its depth in this region ranges from 2,100 feet in southwestern Leelanau County to an estimated 4,300 feet in southeastern Crawford County.

DETROIT RIVER GROUP: The most poorly exposed rocks in the Straits area, the Detroit River group, must be considered at this time to afford the best prospects for oil production in northern Michigan, because the three pools in T. 24 N., nearest to the area, produce from Detroit River rocks, and 13 of the 24 wells over 1,000 feet deep in northern Michigan that reached the top of the Detroit River logged "shows" in these beds. A tabulation of wells in northern Michigan reporting "shows" in the Detroit River group follows.

County	Farm	Well No.	Sec.	T.	R.	DEPTHS Below Surface	DEPTHS Below Top D.R.	DEPTHS T.D. of Well	Remarks
Alcona	Kohlman	2	10	26N	7E	2644	431	3015	Oil below lowest salt
	Campbell	1	22	27N	9E	1710	115	1710	Oil after shot
	Kohlman	1	10	26N	7E	2970	770	2988	Oil
Antrim	White	1	31	31N	5W	1733	19	1770	Oil and gas
	Chamberlain	1	14	31N	8W	1861	616	6150	Oil
Cheboygan	Brown	1	12	33N	3W	1165	120	1694	Oil
	Campbell	1	7	34N	1W	600	0	650	Gas
	Cimmear	1	23	35N	1E	502,591	67,156	1178	Oil "smell"
Crawford	Corning	1	22	25N	4W	4120	1005	4650	Oil
Kalkaska	Lawrence	1	12	28N	8W	2177	36	2215	Oil
Leelanau	Heimforth	1	6	28N	11W	1915,1990	483,558	2475	Oil
Montmorency	Rea	1	24	30N	3E	2094	407	2187	Oil
	Crank	1	15	30N	3E	2182	365	2270	Oil

Also, many wells logged flows of water at varying levels in the Detroit River rocks. Obviously, this group contains a number of permeable beds, particularly within the evaporite succession which overlies the basal limestones.

Rocks of Detroit River age either immediately underlie the drift, or are at shallow depths, at the northern end of the Southern Peninsula and adjacent to the northwest and northeast coasts of northern Michigan. The elevation of the base of the group drops from 600 feet above sea level in the Straits area to 4,600 feet or more below sea level in the center of the Basin.

The Richfield "pay" zone in the Richfield pool is an 8-foot brown "lime" (probably dolomite) which is 1,026 feet below the top of the Detroit River group. It is apparently at the base of the evaporite succession, for 21 feet of limestone has been drilled below the oil-producing zone. In the East Norwich pool the Richfield zone is a brown dolomite 1,066 feet below the top of the Detroit River group. This is near, but not at, the base of the evaporites, for a little anhydrite has been found in samples from underlying rock. About 80 feet of dolomite and limestone containing scattered sand grains was drilled into below the Richfield zone in the east Norwich pool. These rocks probably lie close to the bottom of the Detroit River group.

The porosity of the Richfield zone is due either to original porosity in a dolomite bed or to dolomitization of an original limestone bed. The zone is in the lowest part of the evaporite succession above the basal limestone beds. In the Crank well in Montmorency County the oil is in a brown dolomite 372 feet below the top of the Detroit River group. This dolomite underlies a bed of salt. Reliable data are not available regarding the rocks beneath the oil-yielding zone, so the position of the zone in the evaporite succession cannot be definitely determined. However, the Nevins well to the northeast in Alpena County is higher on the flank of the Michigan Basin and it penetrated 610 feet of evaporites and 60 to 80 feet of basal Detroit River limestone beneath. Therefore it is reasonable to assume that the oil zone in the Crank well is near the middle of the evaporite succession. Only a well drilled through the Detroit River evaporites on the Montmorency anticline can be considered an adequate test of the Richfield zone.

In conclusion, at least two zones in the Detroit River evaporite succession offer possibilities for oil production in northern Michigan. The lower zone, lying near the bottom of the evaporite beds, has already proved productive in a half dozen fields in central Michigan. Toward the rim of the Michigan Basin the evaporite succession thins and eventually disappears, so that only the basal limestones remain in the Detroit River section. In the same area the porous zones in the evaporite succession wedge out on the flank of the Basin. The average dip of these beds pinching out updip is over 50 feet per mile, which is more than sufficient for oil migration. If the porosity of the dolomites in the Detroit River evaporites is at all consistent laterally, the flanks of the Basin in northern Michigan may contain oil fields of the "stratigraphic trap" type. In addition to stratigraphic traps, anticlines doubtless are in northern Michigan which offer distinctly favorable chances for oil accumulation in porous zones of the Detroit River group. Probably very few of the 15 wells (over 1,000 feet deep) in this region that reached the lower Detroit River strata were drilled near the top of the anticlines.

MACKINAC BRECCIA: The most porous rocks in the succession cropping out in the Mackinac Straits area is the Mackinac breccia. Springs are abundant around the borders of the breccia masses on St. Ignace peninsula and Mackinac Island. The indurated breccias are as porous and permeable as a conglomerate, and the non-indurated breccias are as porous as loose sand. Even the megabreccia blocks, because of their extensive fracturing, are more permeable than the undisturbed rocks. The St. Ignace No. 2 and the Cheboygan wells logged water in the breccia section, and the Frankfort (Benzie County) well reported a flow of 8,000 barrels of water a day.

The possibilities of oil storage in the Mackinac breccia are decidedly limited. Over a considerable area (fig. 14) the breccia masses extend to the bedrock surface, so lack an impervious cap. Farther south, however, the Dundee overlies the breccia and the rocks near the base of this formation are sufficiently impervious to serve as a cap rock. Everywhere the top of the breccia is at a relatively shallow depth. The maximum known depth of the Dundee-breccia contact is in the Overby well in Leelanau County, where the top of the breccia is about 1,400 feet below the surface.

HIGHER FORMATIONS: In the southern and central parts of the area the Dundee and higher formations are at sufficient depth to permit commercial accumulation of oil and gas. The Dundee, up to 1945 the number one oil-producing formation in Michigan, is at a depth of 2,695 feet in southeastern Crawford County. Shows of oil and gas have been found in this formation in northern Michigan. The Traverse group, which immediately overlies the Dundee, ranks second in oil production in the State. Above the Traverse is the Antrim shale. Seepage of gas from the Antrim shale into the overlying glacial drift in Montmorency County has been known for many years. The logs of two wells in Alpena and Alcona counties record gas shows in the Antrim. Higher in the column is the Berea sandstone[3] which produces both gas and oil in central Michigan. A well at Harrisville, Alcona County, reported a gas show in the Berea. The stratigraphically highest gas show noted was in the Coldwater shale in a well drilled near Roscommon, but in Crawford County (sec. 31, T. 25 N., R. 2 W.).

OIL AND GAS POSSIBILITIES BY AREAS

The area of probable post-Niagaran, pre-Dundee collapse is shown in figure 14. The northern boundary of the collapse zone as shown is fairly accurate. The line showing the southern boundary, however, was drawn by interpolating between widely scattered central points, and should be considered only as an approximation. The line showing the base of the Dundee formation was drawn largely from well records, as exposures are scanty in this region. Between the base of the Dundee and the northern border of the collapse zone the breccia is at the surface, or immediately beneath the superficial deposits, but to the southern boundary of the collapse zone the breccia is unconformably overlain by Dundee and younger rocks.

Because of differences in the problems involved, the region is subdivided into four areas: 1. The area north of the collapse zone; 2. the area in which the collapse materials are at and below the bed rock surface; 3. the area in which the collapsed materials are covered by younger rocks; and 4. the area south of the collapse zone.

AREA NORTH OF THE COLLAPSE ZONE: Oil production from Trenton and Cambro-Ordovician rocks at shallow depth is a possibility in Mackinac and southern Chippewa counties. The principal advantage for exploration in this area is that the surface rocks are undisturbed. Furthermore, the upper Niagaran rocks, especially of the Engadine formation, are well exposed along the east-west trending Niagaran escarpment. With detailed study of the section it is possible to recognize certain beds which can be used in structure mapping. Anticlines have been mapped on the Niagaran formation and others may be found by surface mapping.

The top of the Trenton is about 800 feet below the surface along the Niagaran escarpment, and the pre-Trenton beds are at a depth of about 1,100 feet.

THE COLLAPSE ZONE AT SURFACE: This area includes most of the St. Ignace peninsula, northern Emmet and Cheboygan

[3]Cohee, Geo. V., and Underwood, Lloyd, Berea sandstone of southeastern Michigan: U. S. Geol. Surv. Prelim. Oil and Gas Investigations, Map 17, 1944.

counties, and northwestern Presque Isle County. Because the breccia forms the bed rock surface it cannot be considered to have oil or gas possibilities. The breccia also completely hides the structural conditions; therefore exploration in this belt should be preceded by drilling to the Niagaran for structural information, or core drilling to a depth of approximately 600 feet in the southern part of St. Ignace peninsula, and to below 2,000 feet depth in north-central Cheboygan county. The Trenton strata, which are at an approximate depth of 2,000 feet, are the most promising formations for oil production on St. Ignace peninsula. Both Trenton and Niagaran rocks merit testing in Emmet, Cheboygan, and Presque Isle counties north of the Dundee boundary. In these counties structure drilling is expensive, owing to the fact that here the Niagaran is 2,000 feet or more beneath the surface, but the chances of finding oil are greater. The top of the Trenton in this belt is at a depth of about 3,400 feet and the pre-Trenton rocks are about 3,700 feet below the surface.

COLLAPSE ZONE BENEATH DUNDEE AND YOUNGER ROCKS: Both of the boundaries of this belt (fig. 14) are approximations drawn from widely scattered well data. The north boundary, the lower Dundee contact, is covered with glacial drift from the Lake Michigan shore to near Rogers City on the Huron shore. In this belt the breccia lies between the undisturbed pre-Salina and post-Detroit River rocks. Presumably any folding that occurred after the younger rocks were deposited (the time of major folding in the Michigan Basin) produced anticlines in both pre-breccia and post-breccia rocks. But anticlines in the Dundee and younger rocks might also be reflections of the topography of the breccia surface. Due to difference in hardness between the non-indurated and the indurated breccias, and between the "let-down" megabreccia rocks and the surrounding rock, the modern topography of the breccia surface on St. Ignace peninsula is decidedly rugged. If the pre-Dundee erosion surface was at all uneven, initial dips or differential compaction and settling would produce structures in the younger rocks which would not continue downward into the pre-breccia formations. The many fracture planes and the erratic dips in the Dundee limestone in the Calcite quarry lend support to the "settling" hypothesis. Therefore, anticlines in the Dundee and younger rocks in the area of overlapped breccia should not be considered as anticlines in the pre-breccia rocks until proved so by drilling or by seismograph surveys.

The chances of oil discovery in this belt in the post-breccia rocks are slight because of their relatively shallow depth. The maximum depth to the upper part of the Dundee formation is about 1,300 feet, but commercial production is not impossible at that depth. Another possible oil reservoir rock in this belt is the porous and permeable breccia itself. Where the overlying rocks are arched into a dome, accumulation of oil may have taken place in the breccia. The most favorable prospects for commercial production, however, are below the collapse zone in the Niagaran and older rocks, which lie within drilling depths (4,095 feet to the top of the Niagaran in the Overby well in Leelanau County) and are not too far from points where it is known that the rocks are porous.

SOUTH OF THE COLLAPSED AREA: The greater part of the area north of T. 24 N. is south of the belt of collapsed rocks. In this region the Salina salt has not been leached, no breccia is in the section, and the anticlines at the surface are probably over anticlines in the older rocks. In the south central part of the area nearest to the center of the Michigan basin, the top of the Dundee formation is at a depth of about 3,000 feet; the Richfield zone of the Detroit River group at about 4,000 feet; and the Niagaran and older rocks are much deeper.

Information available in 1944 and drilling results in the nearby East Norwich, Richfield, and Rose City fields, and in Montmorency County, lead to the belief that the most favorable prospects for production in the area north of T. 24 N. is in the Detroit River dolomites. In the central part of the area accumulation in anticlines (as in the fields to the south) is probable. Farther out, toward the rim of the Basin, "wedge-outs" of the porous zones are possible. Also, in this outer zone, the older rocks lie within reasonable drilling depths.

The Sylvania formation although not elsewhere in the area may be found beneath the surface in the southwestern part, and is another potential oil reservoir rock. Accumulation of oil in the Sylvania sandstone could take place either in anticlines or where the sand lenses pinch out to the north and northwest.[4] The Sylvania is 2,100 feet below the surface in southwestern Leelanau County.

Alpena County is in the area south of the collapsed rocks. In Alpena County the glacial drift is thin and almost continuous exposures of bed rock make it possible to determine structure by planetable mapping, on the various units in the Traverse group. If an anticline of reasonable size were found in Alpena County it

[4] Landes, K. K., Geology and Oil and Gas Possibilities of the Sylvania and Bois Blanc Formations in Michigan; U. S. Geol. Survey Oil and Gas Inves. Prelim. Map 28, 1945.

would be well worth prospecting. The Nevins well in northwestern Alpena County struck the top of the Dundee at 458 feet depth, the Detroit River at 605 feet, the Bois Blanc at approximately 1,290 feet, the Bass Island at 1,700 feet, the Salina at 2,035 feet, the Niagaran at 4,115 feet, the Trenton at 5,145 feet, and the Cambro-Ordovician at 5,650 feet.

CONCLUSIONS

Because the Dundee, which is the leading oil-producing formation of Michigan, rises to the surface in northern Michigan, this part of the State has been almost ignored as possible oil-bearing territory. As a matter of fact, exploration in Michigan has suffered from the twin dogmas—"no good fields are to be found outside of the central part of the Basin," and "there is no oil in any quantity below the Dundee." History has shown analogous statements made elsewhere to be untrue. Experience in other basins and monoclinal areas has shown that oil is no respecter of formation names, or even of geologic age. As oil-bearing formations rise toward the surface, the oil reservoirs in many places drop stratigraphically, so that flank production is obtained from formations older than those exploited at the center of the basin.

The older formations on the northern Michigan "rim" and the younger rocks north of T. 24 N. have not (up to 1945) been adequately tested. By scientific prospecting with core drill and seismograph throughout northern Michigan more oil pools might be discovered.

LIMESTONE

Limestones are absent in the Pointe aux Chenes and St. Ignace formations so the outcrop areas of these rocks have no possibilities for limestone production. The uppermost part of the Bois Blanc formation is limestone which as shown by well records exceeds 150 feet in thickness. It is much thinner at the outcrop, but a close estimate of its thickness there could not be obtained. Many years ago a relatively small amount of Bois Blanc limestone was quarried from near the mouth of Mill Creek in the center of the north ½ of Private Claim No. 344, Cheboygan County. On the upland nearby, deep in second growth timber, in the center of the E½ sec. 29, T. 39 N., R. 3 W., a shallow trench was dug for 500 feet across the outcrop of Bois Blanc limestone very near the top of the formation by parties interested in possible commercial development.[5] However, the entire area of Bois Blanc outcrop is in the zone of collapse and for that reason quarrying would be expensive. The dip of the strata in the Mill Creek quarry is 9°. Furthermore, the Bois Blanc below this uppermost zone is extremely cherty.

Limestone is in the lower part of the Detroit River formation in the northern part of the Southern Peninsula as shown by well records and by outcrops in the NE¼ NW¼, sec. 2, T. 38 N., R. 4 W., Emmet County, where the rock is probably at or very close to the base of the Detroit River formation. With this possible exception, the Detroit River rocks do not crop out, and we know from well records that a deep valley was cut into the Detroit River outcrop in pre-glacial times across the northern end of the Southern Peninsula. This valley is now filled with about 400 feet of glacial drift. Therefore, Detroit River limestones are, in the main, inaccessible. Furthermore, this formation also collapsed like the underlying Bois Blanc.

The formation which has been proved a source of limestone is the Dundee. The Dundee, with the overlying Rogers City limestone, is quarried in the largest limestone quarry in the world, at Calcite near Rogers City in Presque Isle County. The Dundee formation (see geological map, in pocket) is immediately beneath the glacial drift in a gently curving outcrop band extending westward from just north of Presque Isle on Lake Huron to the north side of Little Traverse Bay on Lake Michigan. The covering mantle of glacial drift is thick over the western half of the outcrop but between Black Lake and Rogers City the overburden is much thinner,

[5]According to R. A. Smith, State Geologist, this stone averaged over 93 per cent $CaCO_3$ with some ledges running over 97 per cent.

and it is quite possible that commercial stone is at quarryable depths at places in this area. In fact, good stone prospects may be within a reasonable distance of Grace Harbor, one-time important lumber shipping port. Between Rogers City and false Presque Isle the Dundee is at or very close to the surface.

DOLOMITE

The oldest formation in the area of this report, the Pointe aux Chenes, contains dolomite beds, at the top and near the base. The top dolomite beds are exposed at various places on the southern part of St. Ignace peninsula (see sections in chapter on Stratigraphy of Surface Rocks). The dolomite beds are not thick, and are interbedded with green and red shales. Furthermore, they are all in the megabreccia so do not have lateral continuity. For these reasons the Upper Salina dolomites are not considered to have commercial possibilities. The dolomites in the lower Pointe aux Chenes have one advantageous factor—they lie below the salt zone and therefore are not brecciated. However, these dolomites are relatively thin and are interbedded with shales. Chert was found in the dolomite at one locality, in the south center of sec. 12, T. 42 N., R. 4 W., where pinkish dolomite and cherty dolomite crop out in the bed and cause the rapids of Carp River. Another lower Pointe aux Chenes dolomite locality is on the right bank of Carp River near its mouth in the NW¼ NE¼ sec. 20, T. 42 N., R. 3 W. This outcrop consists of greenish gray, mottled pink dense dolomite and indurated shale.

The St. Ignace dolomite series is the only one thick enough to be quarried. Many years ago the uppermost dolomite beds in this formation were quarried in two places, near St. Ignace and on Mackinac Island. The St. Ignace quarry is about 500 feet south-southeast of the corner of Pero and Hombach streets, St. Ignace. The dolomite which is at least 32 feet in thickness, was quarried from the side of a bluff. The area is now grown over with trees and undergrowth. The disposition of the small amount of stone removed is not known.

The dolomite from Mackinac Island quarry was burned in a near-by lime kiln and used in the construction of the fort. The old quarry is about 750 feet east of the lime kiln, on the opposite side of the Fort Mackinac-Sugar Loaf carriage road. About 6 feet of dolomite is exposed in the quarry face. The bed was worked for many feet along the outcrop. Other exposures of dolomite can be found in this vicinity, especially along Limekiln Trail and northeast of the kiln.

At St. Ignace and on Mackinac Island the dolomite is in blocks in the megabreccia. Therefore, it is unlikely that the dolomite has much lateral continuity. Trans-formational breccia is abundant in the vicinity of both quarries.

The only dolomite deposits which the writers believe have any commercial possibilities are the St. Ignace beds on Round and western Bois Blanc islands, although the amount of stone available above lake level is limited. One of the rock strata contains a few sand grains, which gives that layer a relatively high silica percentage, but the silica content for the entire dolomite section is low. The magnesia content, however, is high. Although these rocks also are in the megabreccia, the dips are moderate, and no transformational breccia was found on either island.

On the east side of Round Island near its highest point is a steep cliff, the top of which is 76 feet above lake level. On the face of the cliff a thick section of St. Ignace dolomite is exposed—the sandy zone is 11 feet below the top. Between the cliff and the lake shore is a lower bench consisting of "gashed" dolomite, which is characteristic of the lower St. Ignace section. Apparently the higher part of Round Island is underlain by a thick block of dolomite. The total tonnage of stone available is considerable, but by no means unlimited. The entire island is owned by the U.S. government. A lighthouse is built at the end of the point at the northwest extremity of the island.

Dolomite outcrops were found on Bois Blanc Island at various places on the western and northern shores. On the northwest shore 500 feet south of the westernmost point in sec. 14, 18 feet of St. Ignace dolomite is above lake level—the upper 10 feet is exposed on the face of a low shore cliff. This rock apparently extends under the low western end of the island and has very little overburden. Along the north shore of the island, in the N½ NE¼ sec. 9, a thirty-foot cliff of dolomite, beginning 5 feet above lake level, is exposed. This section includes the brown somewhat "punky" dolomite of the upper St. Ignace and the gashed cream-colored dolomite of the lower part of the formation. Possibilities of a profitable quarry development are lessened by the fact that 300 feet inland, lower Bois Blanc chert is exposed in a 15-foot cliff. Thus, a dolomite quarry could extend but 300 feet from the shore. The higher cherty rocks swing westerly across the island. Therefore, only the low lying northwestern end of the island is a possible site for a dolomite quarry. A considerable tonnage of stone may be present, but it would be necessary to quarry over a wide area, thus development of a profitable quarry in this locality is probably not feasible.

Further southeast along the shore of Bois Blanc Island, in the northern part of the NW¼ sec. 8, more dolomite is exposed, but the overlying chert is nearer lake level than in section 9 and drops down to beach level about one-half mile farther to the southeast.

The dolomite in the Bois Blanc formation is invariably cherty. The only exposures of the Detroit River formation found in northern Michigan are limestone. High-grade dolomite beds must be somewhere within this formation, since dolomite is in the breccia at Calcite. According to well records, these dolomites are in the upper Detroit River (of northern Michigan), and their natural outcrops are buried beneath thick deposits of glacial drift.

SALT

Many wells in Michigan have drilled into salt in the Salina (Pointe aux Chenes) formation. The map (fig. 3) shows the aggregate thickness of salt in the northern half of the Southern Peninsula. Only a few widely separated wells have penetrated the entire salt series in this area, therefore, factual information is meagre and much interpolation was necessary in constructing the map. The thickest salt so far discovered in Michigan is in the Gulf Oil Company's Bateson No. 1 well in sec. 2, T. 14 N., R. 4 E., Bay County, where several salt beds between depths of 5,480 and 8,260 feet have a total thickness of approximately 1,600 feet. The nearest record to the north is from the C. W. Teater Nevins No. 1 well in sec. 18, T. 32 N., R. 6 E., Alpena County, where the aggregate thickness of salt is 1,200 feet. About 14 miles northeast of the Nevins well, sec. 8, T. 33 N., R. 8 E., Presque Isle County, the Alpena Land Company well penetrated 290 feet of salt and stopped in the Salina formation. On the western side of Presque Isle County, the Chandler well, drilled by the Presque Isle Development Company in sec. 5, T. 34 N., R. 2 E., drilled through a total of 835 feet of salt. The McArthur Brothers well in Cheboygan City, which was drilled in 1901, allegedly found some salt, but none is in the samples from this well. Because of this reported occurrence the zero isopach has been drawn through Cheboygan.

Apparently the Salina salt is thinner on the Lake Michigan side of the Southern Peninsula. The log of a well drilled in sec. 14, T. 31 N., R. 7 W., Antrim County, records 380 feet of beds of salt and shale, and two beds of salt 50 and 160 feet thick. According to its log, a well drilled in sec. 5, T. 29 N., R. 12 W., Leelanau County, penetrated 176 feet of beds of salt and shale and four beds of salt that total 97 feet in thickness. Farther to the south, at Manistee, 524 feet of Salina salt is indicated from well samples.

The isopach map suggests rather strongly that the deepest part of the Salina salt basin may be north of the Bateson well and that in the deepest part the aggregate salt thickness is even greater than 1,600 feet. This deepest part of the basin may contain potash salts, which are of considerably greater value than common salt. It is improbable that the potash-bearing mother liquor of the evaporating Salina sea had an opportunity to escape from the basin after the sodium chloride had precipitated. But it is probable that potash and other highly soluble salts were deposited in the lowest part of the basin—an area which has not yet been explored by the drill.

Salt is also in the Detroit River formation, but the beds are thinner and the aggregate thickness and areal extent are less than in the Salina. The most northerly discovery of Detroit River salt is in the Crank well in sec. 15, T. 30 N., R. 3 E. The thickness of the salt in this well is 140 feet. Earlier in this report it was pointed out that the Detroit River salt may be reworked Salina salt from near the rim of the Salina basin. If that is true, potash would not be in the Detroit River formation.

In conclusion, the northern half of the Southern Peninsula, excepting the tip and the northwestern edge, contains abundant salt, much of it at moderate depths. Salt is such an abundant commodity in the rocks of the earth's crust that it has no value in the ground. The price paid by the consumer is largely the sum of extracting, processing, packaging, marketing, and transportation costs.

GYPSUM

No gypsum within reasonable quarrying depth is available in the far northern part of the Southern Peninsula. North of the Straits, however, gypsum beds in the Pointe aux Chenes formation are close to the surface. The commercial possibilities of these beds were surveyed by Grimsley[6] in 1904.

Gypsum has been quarried at only one locality in the Straits area. According to Grimsley:

> "In the 50's there was a gypsum quarry opened on the west side of the peninsula, seven miles west of St. Ignace near Point Aux Chenes, and a dock was built for loading the gypsum on boats carrying the rock to Chicago, where it was calcined. A scourge of smallpox caused a temporary abandonment of the work, and water in the quarry was a continual

[6]Grimsley, G. P., The Gypsum of Michigan and the Plaster Industry: Michigan Geol. Survey, vol. 9, part 2, chapter 5, 1904.

source of trouble. It was worked in an interrupted way for a number of years, until an ice gorge carried away the dock and the quarry was abandoned. The property is now owned by Chicago parties, but no work has been done for many years.

"About 1894 the Keystone Plaster Co. of Chester, Penn., drilled some test holes about two miles west of the old quarry. The records of this work seem to have been lost, but it is stated by some of the men engaged on that work that 60 feet in all of gypsum were found in these wells, and the first ledge of a few feet in thickness was struck under a light cover. No development has followed this drilling."[6]

The writers were guided to the scene of these operations of 90 years ago by Mr. Robert D. Beveridge of St. Ignace. The so-called "plaster beds" pits are a short distance west of the head of Poupard Bay between highway U.S. 2 and the beach in the W½ SE¼ sec. 31, T. 41 N., R. 4 W. No gypsum is visible in the old pits, but some was found in an old dump which is crossed by a faintly marked road that runs from the highway to the beach.

Rabbit's Back, four miles north of St. Ignace, is a mixture of transformational breccia and megabreccia. The lowland surrounding it is underlain by shale and gypsum. Grimsley stated: "The gypsum in this point outcrops near the water's edge and can be seen under the water near the shore."[6]

Farther north along the shore other exposures of gypsum are reported by Grimsley:

"Gypsum was found at Gros Point four miles north of Rabbit's Back and its outcrop is seen near the shore from this point on to the east for several miles."[6]

Bigsby[7] and Grimsley found gypsum on St. Martin Island, but Rominger[8] and the writers did not. Bigsby and Grimsley probably explored the area when lakes Michigan and Huron were at a low level and rocks on their floors were better exposed. According to Grimsley:

"Some gypsum exploration was carried on a few years ago on St. Martin Island to the east of Rabbit's Back, and the rock shows in the water and was found in shallow wells over a large portion of the southern part of the island. The rock by analysis shows 98 per cent of gypsum, and so contains very little impurity. The records at hand would indicate good deposits which could be worked to advantage if the water could be kept down in the mines at a reasonable cost. The rock on St. Martin Island is stated to be three feet thick in the ledge close to the surface, with other layers further down."[6]

Two wells were drilled in the vicinity of St. Ignace. In the log of the northern well, in sec. 31, T. 41 N., R. 1 E. several beds of gypsum are recorded, including a 13-foot stratum at a depth of 174 feet.[6] As the regional dip is to the south this bed must be closer

[7]Bigsby, John J., Notes on the Geology and Geography of Lake Huron: Geol. Soc. London Trans. (2), p. 193, 1821.

[8]Rominger, Carl., Paleozoic Rocks (Upper Peninsula): Michigan Geol. Survey, vol. 1, pt. 3, p. 30, 1873.

to the surface farther north. Possibly the same bed was penetrated in a well drilled on the Underwood farm near Evergreen Shores north of St. Ignace where "8 or 10" feet of the gypsum was found at a depth of 80 feet.[9]

The following conclusions regarding the gypsum prospects of the St. Ignace region are drawn by Grimsley:

"The objections to the St. Ignace gypsum deposits, that they are in thin veins and of poor quality, are apparently untrue. The evidence at hand does not accord with these rumors. The price of fuel might prevent the manufacture of plaster in this section of the State though water transportation is available, but the gypsum might be mined and shipped to other points further south. At the present time there is no development of these gypsum fields."[6]

The writers are not quite so optimistic as Grimsley. The gypsum bearing rocks are in the zone of collapse, therefore, the gypsum beds are probably tilted and faulted and not continuous. Furthermore, all of the known gypsum beds are below lake level, and to quarry gypsum from them would involve very high, perhaps prohibitive, pumping expense.

[9]Beveridge, Robert D.: Oral communication.

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