REGIONAL STUDY OF THE UPPER SILURIAN, SALINA EVAPORITES IN THE MICHIGAN BASIN

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ABSTRACT

REGIONAL STUDY OF THE UPPER SILURIAN, SALINA EVAPORITES IN THE MICHIGAN BASIN

By James William Burns

The regional study was conducted to consolidate and analyze the dispersed information which has become available on the Salina formation primarily since 1945. Geographically this work encompasses the southern peninsula of Michigan. A series of fifteen maps and cross sections were constructed of the various units of the Salina formation. These maps were based primarily on the sample logs from 358 oil and salt brine wells drilled in the Michigan Basin.

A practical application of this work is a disscusion of the possible use of several of the Salina evaporite units as underground, radioactive waste disposal containers. Geologically a large lateral area was found to exist in Michigan in which a radioactive waste disposal site could be established. The A-2 and B-Evaporite units possess significant radioactive waste disposal potential.

The hundreds of feet of Salina evaporites were deposited in a shallow, restricted sea. The climate during Salina time was rather arid with a very high average daily temperature.

James William Burns

The importance of the Chatham Sag area as a major source of seawater to the Michigan Evaporite Sea is recognized. The Michigan Basin continually shifted toward the east and later toward the northeast during Salina time. There is excellent evidence for the elevation of the Salina formation to group level.

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By

James William Burns

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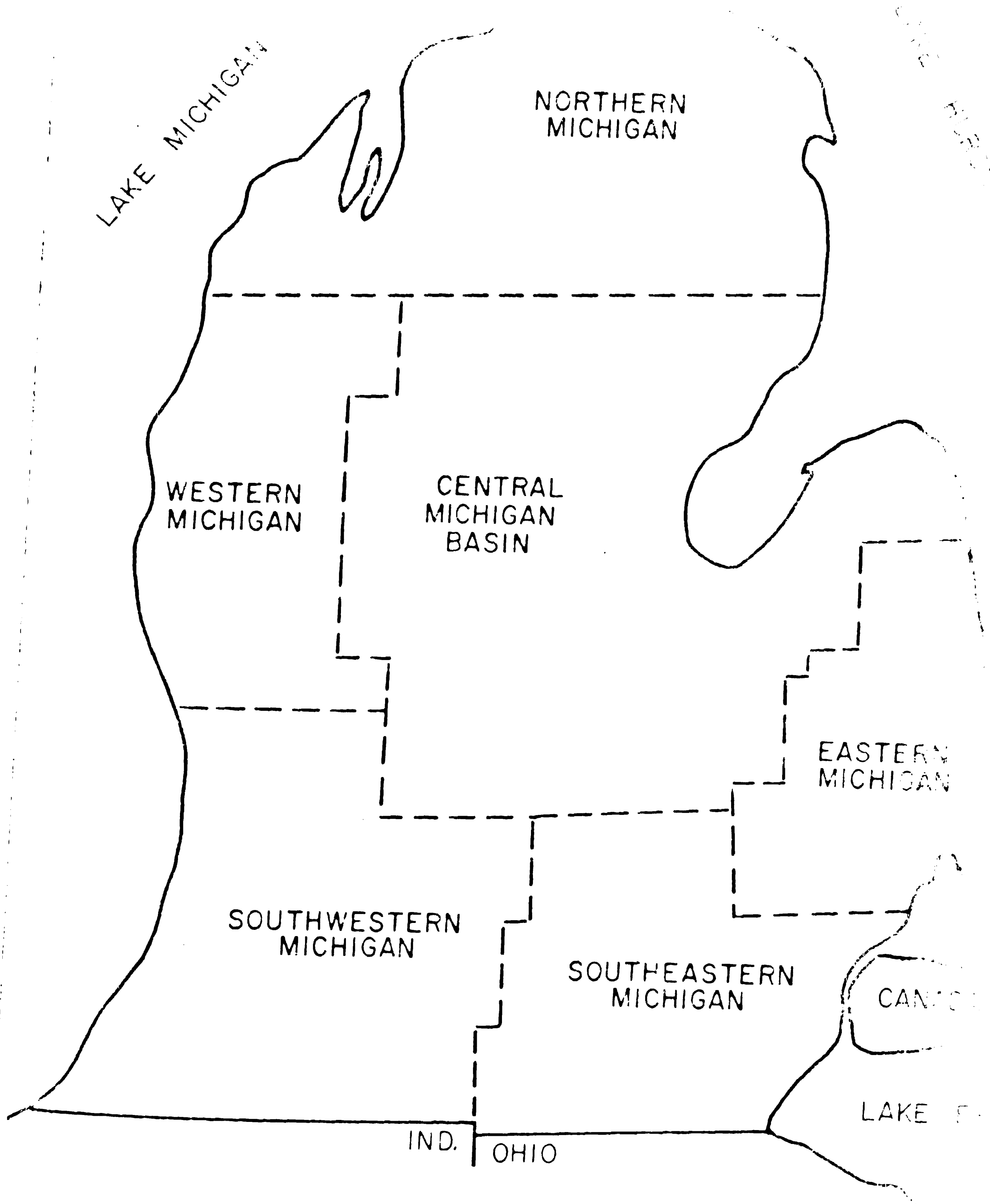
INTRODUCTION

The purpose of this study is two fold. The major purpose is to bring up to date and expand the work of Kenneth Landes's original decription of the various members of the Salina formation. There is also incorporated several recent works on the origin and distribution of the upper Silurian. The great number of deep tests which have been drilled since Landes's work was published makes this study feasible (Landes, 1945).

Though this study has important economic relationships to the oil, gas, and salt industries; another consideration is the possible use of the Salina formation as a radioactive waste disposal container. Since salt units seem to have unique features which favor them as valuable radioactive waste disposal sites; this seems a worthy sector of geologic study.

This regional study was conducted over the southern peninsula of Michigan with major emphasis on that portion of the southern peninsula in which evaporite units were developed during Salina time. Figure 3 pictorially notes this area. When various sectors of the Michigan Basin are referred to, such as the southwest, an examination of Figure 1 should make these relative areas clear.



LOCATION OF DISTRICTS
(FIGURE ONE)
(MODIFIED FROM IVES AND ELLS, 1957)

The majority of the information used in preparing the included maps and cross sections was obtained from 358 sample logs. These sample logs were prepared and are on file at the Michigan Geological Survey, Lansing, Michigan. Detrailed descriptions of several cores in Kent, Newaygo, and Wayne Counties were also studied.

In a number of cases the tops of the various units, as picked by the Michigan Geological Survey, were in disagreement with those of my own. This was generally only the case in those deep tests which were described before 1950. Since the terminology of several members of the Salina formation has gone through an evolutionary process, this would be expected. When electric or radioactivity logs were available they were checked to see if a discrepancy did exist.

The wells completed during 1960 posed a special problem since the sample logs on many of them have not been completely prepared. In as many cases as possible this problem was overcome by the examination of the scout tickets and the related radioactivity logs. The deep tests used in this work are complete through January 1961.

The Salina formation composes approximately thirty per cent of the aggregate thickness of the sedimentary rocks found in the Michigan Basin. The Salina formation is represented in the Michigan geologic column as most of the upper Silurian system or Cayugan series of Michigan. This formation is composed mainly of thick evaporite units interbedded with shale and carbonate units. As a result of earlier investigations it became apparent that the Salina formation could be divided into a number of distinct members which can be traced throughout most of the Michigan Basin (Landes, 1945). These members have been labeled alphabetically from A through G with the A members representing the basal units of the Salina formation. To complete the upper Silurian, the Bass Island group has been termed the H-unit (Landes, 1945). The original subdivision of the Salina formation has changed somewhat during the past fifteen years as more information became available on the Michigan Basin. For example the original A unit has been divided into four distinct members.

Several terms are often referred to which demand explanation. The term Michigan Basin refers to the total area which was covered by the Michigan Sea as its limits were defined in the upper Silurian. The term Michigan Evaporite Basin is restricted to that portion of the Michigan Basin in which evaporites were deposited during Salina time. The hingeline of the Michigan Basin has been correlated with the zone of sudden thickening of the evaporite units. The term Southern Carbonate Shelf, first used by Briggs (1958), notes that portion of the Michigan Basin south of the evaporite pinchout (Figure 3).

HYPOTHETICAL BASIN DEVELOPMENT

Formation of an Interacratonic, Evaporite Basin

In much of the literature published on geosynclines by Kay (1951), Sloss, and Krumbein (1955), the Michigan Basin has been noted as the prototype of the autogeosyncline or intracratonic basin. The isolated intracratonic basin generally is represented as an ovate area in which the rate of subsidence decreases outward from the center of the basin. The sediments deposited are mainly composed of fine clastics derived from a distant source or abundant carbonate rocks often associated with major evaporite units (Krumbein, Sloss, and Dapples, 1949). An intracratonic basin is generally not completely restricted from surrounding seaways through its existance. There are periods of normal sea circulation producing typical marine deposits. There are other intervals in which surrounding positive features or the development of biohermal banks restrict circulation thereby developing thick evaporite sequences (Krumbein, Sloss, and Dapples, 1949). These thick salt sequences are associated with arid or semiarid climtes such as presently exist in the deserts of Arizona or California (King, 1947).

Deposition of Evaporite Units

The problem of how thick beds of salt are formed has puzzled geoligists for many years. Ochsenius (1888) developed the Bar Theory to explain massive salt deposition. Branson (1915) and King (1948) suggested modifications to Ochsenius's theory which more fully explained geologic observations.

King explains the problem presented by the presence of about a one to one volume ratio of calcium sulfate to sodium chloride as observed in the Permian, Castile beds of West Texas. The problem is that the ratio in normal seawater is about one volume of calcium sulfate to thirty volumes of sodium chloride. King noted that the Permian-Delaware Basin of West Texas and New Mexico was an arid region in which evaporation greatly exceeded the influx of local meteric waters. The evaporation rate also exceeded the influx of normal seawater through a restricted channel. The water in the basin which was below average wavebase consisted of a uniform brine formed by the excess of evaporation. At intermittent times normal marine waters flowed into the basin through the restricted channels and flowed over the uniform brine across the basin. Slowly by evaporation the newly arrived water was concentrated to a brine similar to the density of the underlying solution. As a compensation for the volume of sinking brine, King suggested a continuous seaward flow of dense hypersaline water as reflux out of the basin (King, 1947).

Since in the Michigan Basin the amount of sodium chloride (common salt) far exceeds the amount of calcium sulfate (anhydrite) the reflux of hypersaline water is not entirely neccessary to explain the evaporite sequence. This point can later be used to show that the Michigan Evaporite Sea was more restricted than the Castile Sea.

Scruton has stated that high brine concentrations are associated with a strong salinity gradient which produces the lateral segreation of the various precipitated salts. The escaping deep current returns to the open sea those salts which have not been precipitated (Scruton, 1953). Fluctuations in the delicate equilibrium caused by changes in excess of evaporation or in the width, depth, or number of channel openings cause migration of the horizontal salinity gradient along the longitudinal axis of the basin. This process produces vertical differentiation of the various evaporites (Scruton, 1953). He also noted that the order in which the evaporites are precipitated in the vertical column not only can be predicted from studies of estuaries and lagoons which presently exist, but agree with the vertical sequences described in several Paleozoic formations. Scruton's horizontal gradient produced the following sequence of deposition. First a carbonate should be deposited, then anhydrite, then halite with anhydrite, and at last nearly pure halite. The following conclusions were reached by Scruton on the deposition of evaporites (Scruton, 1953).

1. Evaporites are deposited in restricted arms of the sea in areas where evaporation exceeds precipitation.
2. Circulation in the basin is established similar to that a continuous inflowing surface current of partly concentrated solution is counterbalanced in part by a continuous return flow at depth of concentrated brine toward the sea.
3. High salinity is developed because of restriction to brine escape. The brine which does escape when equilibrium conditions are established returns to the open sea those salts which have not been precipitated.
4. Restrictions to escape of the deep brine are in part static (as physical barriers) and in part dynamic (as relationship between pressures due to hydrostatic head and density distribution, friction between currents flowing in opposite directions, and friction between the deep current and the channel botton. The basin equilibrium is dynamic and is principally sensitive to fluctuations of excessive evaporation and degree of channel restriction.
5. The vertical sequence of beds which results from salinity changes can be predicted approximately from experiment on evaporation of seawater.
6. Extreme fluctuations in the precipitations-evaporation budget, so that precipitation and runoff are predominant, can result in a change from conditions of a euxinic basin within the same physical framework.

HISTORY OF DEPOSITION OF THE MICHIGAN SILURIAN

Deposition During the Silurian Period

The Silurian period was ushered in by a widespread marine transgression from Canada to the north. This marine invasion is represented by the Manitoulin carbonate (Newcombe, 1933). These sediments show normal marine deposition indicating that the Michigan Basin was not a distinct feature in Manitoulin time. The Kankakee and Findlay Arches, which are believed to be Ordovician structures, apparently existed as slightly positive features which restricted circulation to the south.

The Cabot Head shale which overlies the Manitoulin carbonates was probably derived from clays washed into the Michigan Sea through the Chatham Sag area. Since this shale unit becomes increasingly dolomitic to the north and west, the Chathan Sag provides an excellent avenue through which clastic sediments could have been transported. The red and green color of the shales possibly indicates deposition in a shallow water environment in which circulation conditions were fairly restricted (Melborn, 1958).

The middle Silurian, Clinton shale formation was also the result of an influx of clay muds from the east. This formation indicates increased subsidence and deepening of the marine waters in the Michigan Sea (Melhorn, 1958).

GENERALIZED GEOLOGIC COLUMN OF MICHIGAN
(FIGURE TWO)
(MODIFIED FROM IVES AND ELLS, 1957)

SYSTEM, SERIES	FORMATION, GROUP	LITHOLOGY	THICK-NESS
PLEISTOCENE	GLACIAL DRIFT	SAND, GRAVEL	0-1000
PERMO-CARBONIFEROUS	RED BEDS	SHALE, CLAY	80-95
PENNSYLVANIAN	GRAND RIVER	SANDSTONE	80-95
	SAGINAW	SHALE, SANDSTONE	20-535
MISSISSIPPIAN	BAY PORT	LIMESTONE	2-100
	MICHIGAN	SHALE	0-500
	MICHIGAN STRAY	SANDSTONE	0-80
	MARSHALL	SANDSTONE	100-400
	COLDWATER	SHALE	500-1100
	SUNBURY	SHALE	0-140
	BEREA-BEDFORD	SANDSTONE, SHALE	0-325
	ELLSWORTH-ANTRIM	SHALE	100-950
DEVONIAN	TRAVERSE	LIMESTONE, SHALE	100-800
	BELL	SHALE	0-80
	ROGER CITY-DUNDEE	LIMESTONE	0-475
	DETROIT RIVER	DOLOMITE	150-1400
	SYLVANIA	SANDSTONE, DOL.	0-550
	BOIS BLANC	DOLOMITE, CHERT	0-1000
SILURIAN	BASS ISLAND	DOLOMITE	0-570
	SALINA	SALT, ANHYDRITE, SHALE, DOLOMITE	100-3200
	NIAGARAN	DOLOMITE	75-600
	CATARACT	SHALE, DOLOMITE	50-200
ORDOVICIAN	CINCINNATIAN	SHALE, LIMESTONE	250-800
	TRENTON	LIMESTONE	200-
	BLACK RIVER	DOLOMITE	1000
	ST. PETER	SANDSTONE	0-150
OZARKIAN OR CANADIAN	PRAIRIE DU CHIEN	DOLOMITE	0-410
	HERMANSVILLE	DOLOMITE	15-500
CAMBRIAN	MUNISING JACOBSVILLE	SANDSTONE	200-1700

Niagaran time has been noted as the first extensive subsidence of the Michigan Basin. The Michigan Sea was connected to the Illinois Basin to the south by the Battle Creek Trough thereby permitting relatively free circulation between the two subsiding basins (Melhorn, 1958). The Chatham Sag was also an important link between the Appalachian seaway to the southeast and the Michigan Sea. The light colored, fine-textured carbonates contain various fossils which indicate a normal marine environment. As Niagaran time progressed an increasing number of bioherms were formed along the hingeline of the basin as small isolated, discontinuous structures. As the reefs became more prominent, the importance of the Battle Creek Trough as a link between the Illinois and Michigan Basin diminished. This was probably due to a slight rejuvenation of the Kankakee and Findlay Arches which remained as primarily positive features throughout the upper Silurian. This increased restriction of the basin resulted later in the deposition of the Salina evaporites (Melhorn, 1958).

The upper Silurian, which is represented by the Salina formation and the Bass Island dolomite, began with the widespread deposition of carbonate muds and anhydrite. The deposition of the A-1 evaporite which soon followed indicates the development of a silled or barred basin in which intermittent influxes of normal marine water caused the deposition of carbonates in the predominently salt section of the Salina formation (Dellwig, 1954). As evaporitic conditions became more intense the reef structures of the upper Niagaran or Guelph member of the upper Silurian died out and were overlapped by major evaporite units. These reefs in many places formed dome like or pinnacle structures in the overlying formations which are of economic interest (Ells, 1958).

Geographical Framework During Salina Time

The positive features surrounding the Michigan Basin during the Silurian were the Canadian Shield to the north, the Wisconsin Dome to the west, the Kankakee Arch on the southwest, and the Findlay Arch on the southeast. None of these features was the source of large amounts of clastic material during Salina time. This indicates that these features were at best only slightly positive. Various authors such as Pirtle (1932), Newcombe (1934), and Lockett (1947), are in agreement that most of the regional tectonic features forming the freamework of the Michigan Basin were inherited from the late Precambrian time. Such features as the Kankakee Arch and Findlay Arch are believed to have first become important during the early Ordovician (Melhorn, 1958).

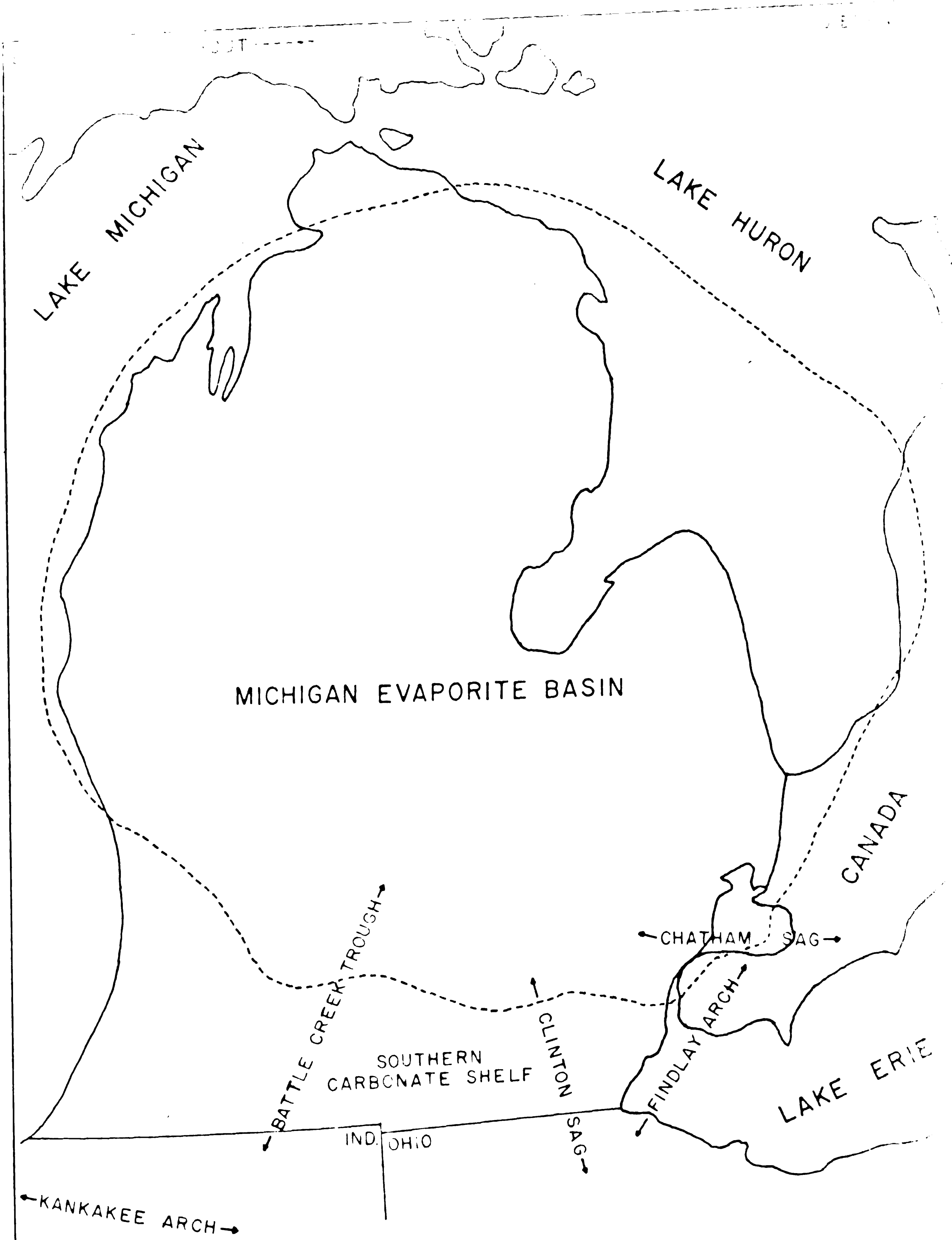
One of the major inlets through which seawater replenished that lost by evaporation was the Chatham Sag. Other than scattered evidence presented by the inclosed maps on the importance of the Chatham Sag as a link to a southeastern seaway the following has been observed.

1. Shaly units in Oakland County, near the Chatham Sag, tend to be thicker and more common than in other parts of the evaporite basin.

2. In the International Salt Mine at Detroit, Michigan ~~the poor development of bedding~~, the poor development of bedding, fragmentation of halite crystals, and the abundance of ripple marks note this area as one of turbulence of seawater (Dellwig, 1954). This would be expected if a current was flowing through the Chatham Sag.

3. The Salina isopach map shows an extensive thickening of sediments in the Chatham Sag area.

The Georgian Inlet located in the present Georgian Bay, Ontario area has been considered as an important possible source of seawater to the Michigan Evaporite Basin during Salina time (Briggs, 1958). Several of the enclosed maps indicate a possible source of sediments from the Georgian Inlet area. Briggs noted that the Clinton Sag



TECTONIC MAP OF MICHIGAN
DURING UPPER SILURIAN TIME
(FIGURE THREE)

could have been a source of seawater into the Michigan Basin during Salina time (Briggs, 1958). The isopach map of the Salina formation indicates thickening of sediments in the Clinton area, but it is doubtful that the Clinton Sag contributed much seawater to the basin. During the deposition of such major units as the A-1 and A-2 carbonates the Clinton Sag might have been a significant source of seawater. The Battle Creek Trough is believed to have been blocked throughout most of Salina time by a slight rise of the Kankakee Arch (Melhorn, 1958).

Origin of the Salina Evaporites

Louis Dellwig made an interesting study on a core from the Glen Bradley No. 2 in Newaygo County and contributed some important information on the origin of the Salina evaporites (Dellwig, 1954). Dellwig's thin section study, which was supplemented by an examination of polished slabs and water-insoluable residues, was conducted mainly on core from the A-1 Evaporite unit. Dellwig determined that pyramidal shaped hopper crystals of halite were deposited during the time of the A-1 Evaporite which are very similar to those formed by nature in salt flats or evaporite pans today. He also noted that these pyramidal forms were outlined by liquid inclusions from which an estimate of the temperature of formation of the salts could be determined. Apparently small bubbles of air were trapped in the crystals as they cooled. By determing when these air bubbles dis-appeared when heated Dellwig was able to state that the salt crystals were deposited at a temperature ranging between 32.0 and 48.4 degrees centigrade (Dellwig, 1954). When converted to Fahrenheit this would mean that the temperature at the surface of the Michigan Evaporite Sea varied between 90 and 119 degrees at the time of the salt deposition. To substantiate these figures, Dellwig noted the presence of Langeinite which is a rare mineral deposited at a minimum temperature of 37 degrees centigrade (Dellwig, 1954). He observed that a warm season produced smaller halite crystals than a cold season. This lead Dellwig to the conclusion that higher temperatures were common during the formation of the A-1 Evaporite than are found in solar salt flats today (Dellwig, 1959).

The extremely high temperatures proposed by Dellwig could be parcially explained by the heating effects of radiant heat (Douglas and Goodman, 1957). Radiant energy can pass through mediums which are transparent to the wave length of radient energy such as semi-fresh water and heat up the more saline solution below due to its lower specific heat. This would make it possible for a restricted evaporite sea to accumulate more heat during the day than it loses during the night (Douglas and Goodman, 1957). The radient energy theory could greatly modify the effects of daily and seasonal variations in temperature.

Dellwig noted that the salt was deposited in three distinct layers.

1. Cloudy layers of inclusion-rich pryamidal shaped hopper crystals of halite.

2. Clear layers of inclusion-free halite, and

3. Laminae of anhydrite and dolomite. These units are in part obscured in the recrystalized salt.

The alteration of bands of clear and cloudy halite was the result of temperature changes, probably related to the seasons. The salt crystals initially formed on the surface, growing as pyramidal shaped hoppers. Until the brine became saturated, settling hopper crystals were dissolved. After the saturation point has been reached pyramidal shaped hopper crystals accumulated on the bottom of the basin to form a layer of cloudy salt. With subsequent cooling the brine passed into the supersaturated state and settling hopper crystals provided nuclei for clear overgrowths.

These crystals which grew on the bottom of the basin are inclusion-free and form layers of clear salt. The return of higher temperatures followed by lower temperatures would cause a repetition of this sequence. This cycle could have been interrupted at any time by the addition of brine to the basin or by periods of unusual climatic conditions.

Dellwig also mentions that there is very little evidence the salt crystals have undergone deformation and this probably indicates that little pore space existed between the salt grains at the time of deposition. Together with recrystallization and original growth the salt beds formed a rigid rock unit (Dellwig, 1954).

Several minerals such as quartz, celestite, polyhalite, pyrite, and graphite are often found in very minor amounts when insoluble residue tests are made. The rare salts are quite unusual for apparently the sequence of precipitation was terminated before the development of the polyhalite phase as suggested in the theoretical sequence of salt deposition (Dellwig, 1954).

Environment of deposition of the Salina formation

There is little evidence of fossil life in the Salina formation. This often mades correlation of some of the members difficult, especially in the area of the Southern Carbonate Shelf. Some evidence of fossil life has been found in the form of long tubes of carbon which closely resemble those of the Devonian-Silurian Prototaxities plant. This form of life is of questionable marine or terrestrial origin (Arnold, 1952).

The following evidence indicates the depth of water in the Michigan Evaporite Sea did not exceed a depth of approximately fifty feet. In fact the average might well be between ten and thirty feet. It is also quite probable that large salt flats existed as slightly positive features in various parts of the sea. These salt flats could have actually separated the Michigan Evaporite Sea into a series of smaller bodies of brine for limited periods as was suggested by (Melhorn, 1958).

Evidence for shallow water origin.

1. The presents of a great number of minute angular unconformities in the salt sections. Several of these have been noted in the core samples of gas storage wells in western Michigan.

2. Presence of ripple marks in the International Salt Mine in the evaporite sections (Kaufman and Slawson, 1950).

3. Presence of a twenty foot shaly conglomerate in southeastern Huron County (Figure 6).

4. The possible presence of wind blown salt in western Michigan; Whitehall Oil Corporation SP22839, Sheridian Twp. #1, 26-12N-14W, (3680-3690 in D-Evaporite) (Ellis, personal communication).

5. The presence of patch reefs scattered over a wide area of the basin in late Nigaran and possible early Salina time.

6. Presence of hematite in small quanitities in association with the salt units. Notes oxidizing conditions indicating formation above wavebase.

From the preceding discussions a summary of the environment of deposition of the Salina formation has been constructed.

1. The tectonic framework existing in the area of the Michigan Sea during Salina time was extremely stable.

2. The Michigan Basin subsided at a relatively uniform rate as sediments were deposited.

3. The lack of large volumes of clastics in the Salina geologic column indicates that the surrounding land masses were only slightly positive features at best.

4. The Michigan Sea during Salina time was predominently isolated from related water bodies.

5. Water lost by evaporation from the basin was mainly replenished through several narrow inlets or troughs.

6. Little organic life existed in the Michigan Evaporite Sea during the time of the evaporite deposition.

7. The average daily temperature was extremely high during the time of salt deposition.

8. The climate during Salina time was apparently quite arid.

9. The water in the Michigan Evaporite Sea was generally under fifty feet deep.

DISCUSSION OF THE MAJOR ROCK UNITS

Discussion of the Niagaran 'Group'

The Niagaran group which underlies the Salina formation is composed predominantly of dolomite though in scattered areas in the Michigan Basin it is composed mainly of limestone. The upper unit of the Niagaran "Group is known as the Lockport Dolomite in the southern two-thirds of the Michigan Basin. In the northern penisula, where the Niagaran Group is exposed, the interval is known as the Engadine formation. The Lockport Dolomite is described in most sample logs as a white to blue-gray dolomite. In various portions of the basin it is light brown to gray-brown. The Lockport Dolomite possesses good porosity and in the Albion-Scipio oil field west of Jackson, Michigan excellent porosity is present along the proposed fault trend. The Guelph-Lockport dolomites contain a great number of biostromes and bioherms. In these reef buildups the porosity varies from extremely vugular to intercrystalline. The vugs in the upper part of the reefs are often filled with salt or anhydrite which is believed to come from the overlying evaporite units (Melhorn, 1958). It is important to note that the reefs found closer to the center of the basin are more commonly salt filled. This is an important factor in the economic exploration for petroleum in the reef zone. This would limit the importance of the reef zone normally to the outerfringe of salt deposition. The reefs formed an undulating topography over which the Salina evaporite units were deposited. They give the effect of buried mounds or pseudoanticlinal structures on structure contour maps of the upper horizons (Ells, 1958). These features are apparent on the various structure contour maps in the St. Clair County vicinity of Eastern Michigan.

Guelph or "Brown Niagaran." This carbonate section varies from ten feet in thickness near the center of the basin to several hundred feet where the reef sections are developed. In the southern portion of the Michigan Basin the drilling term, "Brown Niagaran," has been applied to this distinct brown colored basal carbonate section.

This unit presents a specially difficult stratigraphic problem. Lithologically it seems that the Guelph or "Brown Niagaran" horizon should be included as part of the Niagaran Group. It is probable that the Guelph or "Brown Niagaran" horizon represents the first phase in the progressive evaporite sequence as presented by Scruton (1953). If the latter statement is the case, there is a sound reason for placing this unit as the basal horizon of the Salina formation. Since the accepted top of the Niagaran group is often hard to distinguish except by an examination of the samples, the Guelph or "Brown Niagaran" is sometimes picked as the true Niagaran top on drillers logs. Actually this unit has little significance except in the reef areas. It is difficult to determine if the reef section should all be included in the Guelph or "Brown Niagaran," or only partially included. This horizon does represent an important potential oil and gas pay zone.

Discussion of Niagaran structure contour map. The Howell and Freedom Anticlines appear as very distinct features on this map. These two major anticlinal trends appear to be converging towards their northwestern limits. Several smaller anticlines can be noted in Monroe County which appear to merge with the Freedom Anticline. Two anticlines are evident in the eastern portion of the basin. These two trends appear to be associated with the known bioherms in the Macomb-St. Clair County area.

The regional dip of the basin is fairly uniform except in the northern and northwestern portions of the basin where the regional dip is steeper. The basin is quite ovate with a slight northwest-southeast enlongation. The structural center of the basin is located in central Gladwin County.

A structural low in southwest Hillsdale County and also one in southwest Cass County appear as distinct features. On the Salina structure contour map these features are largely absent since the upper Salina units have been truncated by the disconformity associated with the close of the Silurian.

Salina Formation or Group

There is an excellent case for the elevation of the Salina formation to group level. This would be in line with recent trends in stratigraphy and also in keeping with the present usage by a number of authors. The following evidence is presented for the elevation of the Salina formation to group level.

1. The Salina formation can be readily segregated into ten distinct members which can be traced across most of the Michigan Basin.

2. The Salina formation reaches a maximum thickness of over 3200 feet near the center of the Michigan Basin.

3. The Salina formation represents the majority of the upper Silurian column in the Michigan Basin.

Discussion of the Salina Isopach Map. The isopach map of the Salina formation indicates a basin which is elongated in a northwest-southeast direction. The area of maximum thickness is located in the northwest corner of Arenac County. The approximately 3200 feet of Salina rock proposed for this area is located northeast of the structural center of the basin. This map tends to confirm the shift of the center of deposition toward the east and northeast which is noted in the later discussions of the various maps and cross sections. Though the basin has been portrayed as closed on the northeast it is possible the basin extends farther to the east and northeast than it has been mapped. For example Salina salt units have been commercially exploited for many years along the eastern shore of Lake Huron in Ontario, Canada (Caley, 1945).

The hingeline of the Michigan Basin has been defined as the average line of pinchout of the Salina salt units (Map No. 7). The hingeline of the basin is very apparent on the Salina formation isopach map. The hingeline of the basin is extremely steep parallel to the Howell and Freedom Anticlines. There does appear to be a definite thinning of the sediments over the Freedom Anticline as can be observed by the sharp break of the contour lines over this structure. The Chatham Sag, Clinton Sag, and Battle Creek Trough are apparent features. A rather distinct narrow reentrant can be observed plunging south into Monroe County. The reef structures in the Macomb-St. Clair County area are extremely evident, but all the basinward extentions do not conform with reefs which have been detected at present. Another distinct area of thickening in northern St. Clair County approximates the position of the Port Huron Monocline or fault. There are two anticlinal trends on the Southern Carbonate Shelf, one of which is in the area of the Albion-Scipio oil field and the other to the west of the Battle Creek Trough in Van Buren, Cass, and Kalamazoo Counties. The Van Buren projection hints there might actually be two projections of thin sediments separated by a narrow thick lens of Salina sediments.

The area in Macomb County, which Landes (1945) believed was due to the leaching of the upper Salina evaporites and later collapse of the sediments, is represented by a hachured symbol since the contour interval of 100 feet would be impractical to adhere to in this area. Recent evidence from an unpublished cross section indicates collapse after leaching is not the case (Ells, personal communication). It appears the F-Evaporite units were either not deposited or have been removed so slowly that the interbedded carbonates and overlying Siluriam sediments subsided without losing their identity. This is an interesting area in which more research will have to be done before the actual cause can be safely stated.

In the northern portion of the basin it is difficult to distinguish local structure from the regional dip since few wells have been drilled through the Salina formation. There does appear to be an area of thinner sediments in southwestern Charlevoix County which could represent a local structure.

In the western portion of the Michigan Basin a fairly pronounced wedge of sediments is noted. This is located in Oceana and Mason Counties.

Description of the A-1 Evaporite. The A-1 Evaporite unit is the basal evaporite in the Salina column. It rests upon the Guelph or "Brown Niagaran" carbonate. The A-1 Evaporite is composed mainly of a relatively clear salt section which includes some anhydrite and carbonate. It reaches a maximum thickness of about four hundred feet of relatively clear salt near the center of the basin. Near the flanks of the basin it is represented by an anhydrite section which has a maximum thickness of about thirty feet. The anhydrite grades into a carbonate section as the edge of the Michigan Evaporite Basin is reached.

In those areas where Guelph-Lockport reefs have been developed the A-1 Evaporite generally is not present as a salt unit, but is represented by an anhydrite unit which pinches out over the reefs. This can be noted in the Berlin reef field, the Boyd reef field, and the Peter's reef field in St. Clair County.

The A-1 Evaporite has a much greater westward extent than the other salt units. This is evidence of the continuous shifting of the basin toward the east with the later deposition of younger units.

Description of the A-1 Carbonate unit. The A-1 Carbonate rests directly upon the A-1 Evaporite. It is a dark brown carbonate which is shaly and anhydritic in places. Its thickness vaires between 50 and 130 feet within the area of evaporite deposition. It may not be present over the higher portions of reef sections. This unit may be entirely dolomite or limestone or a combination of the two. No definite relationship between the dolomite and limestone was established relative to geographic position in the basin. It can be advanced that the A-1 Carbonate in the northern and northwestern portion of the basin is composed mainly of limestone though this is not always the case. The texture of the carbonate varies from sublithographic to

GEOLOGIC COLUMN OF THE UPPER SILURIAN
IN THE MICHIGAN EVAPORITE BASIN
(FIGURE FOUR)

FORMATION	MEMBER	LITHOLOGY	THICKNESS
BASS ISLAND OR H-UNIT		DOLOMITE-ANHYDRITE, SHALE	100-600 FT.
SALINA	G-SHALE	SHALE-DOLOMITE, ANHYDRITE	40-120 FT.
	F-UNIT	SALT, DOLOMITE-SHALE, ANHY.	100-1000 FT.
	E-UNIT	DOLOMITE-SHALE, ANHYDRITE	100-170 FT.
	D-EVAPORITE	SALT-SHALE, DOLOMITE, ANHY.	0-80 FT.
	C-SHALE	SHALE-DOLOMITE, ANHYDRITE	30-140 FT.
	B-EVAPORITE	SALT-DOLOMITE, SHALE, ANHY.	0-440 FT.
	A-2 CARBONATE	DOLOMITE-SHALE, ANHYDRITE LIMESTONE-SHALE, ANHYDRITE	100-200 FT.
	A-2 EVAPORITE	SALT-DOLOMITE, ANHYDRITE	0-480 FT.
	A-1 CARBONATE	DOLOMITE, LIMESTONE -SHALE, ANHYDRITE	50-130 FT.
	A-1 EVAPORITE	SALT-DOLOMITE, ANHYDRITE	0-400 FT.
	GUELPH	DOLOMITE, LIMESTONE	10-300 FT.

finely crystalline.

Various horizons of the A-1 Carbonate have been referred to as the "poker chip" shale (Ells, 1958). Cores of particular lenses of this unit split rather easily into thin wafers of chips of about an eighth of an inch thick. The "poker chips" are composed of minute laminae of dark brown, finely crystalline dolomite separated by even thinner carbonaceous partings (Ells, 1958). The "poker chip" horizons also contain thin partings of dark anhydrite. The "poker chips" as described probably represent annual cycles. Changes in salinity due to variations in temperature, evaporation, sea level, or wind could separately or cumulatively have caused the formation of the "poker chips" (Adams, 1944). These "poker chip" horizons are found scattered over much of the southern half of the basin. The porosity of some of thses dolomite laminae is extremely good.

The A-1 Carbonate is much lighter in color and of a more consistent dolomite lithology to the south of the hingeline of the basin. The A-1 Carbonate contains oil and gas pays (Ells, 1960).

<u>Discussion of the A-2 Evaporite</u>. The A-2 Evaporite extends from the top of the A-1 Carbonate to the base of the A-2 Carbonate. It is composed primarily of salt with some

interbedded anhydrite, shale, and dolomite. These impurities are mainly concentrated within the upper 100 feet of the unit. The A-2 Evaporite reaches a maximum known thickness of 463 feet of relatively pure salt to the northwest of Bay County near the theoretical center of the Michigan Basin. The average thickness of this unit is about 250 feet within the area of salt deposition. The A-2 Evaporite grades into a twenty foot anhydrite near the salt pinchout. The A-2 Evaporite has definately shifted eastward from the A-1 Evaporite.

Discussion of the A-2 Evaporite isopach map (Map No. 4). This map notes a maximum known thickness of more than 470 feet of salt in a northwest-southeast elongated basin. A bicentered basin is presented forming an odd horsehoe shape. One center is located in central Gladwin County and the other in southwestern Tuscola County. This horseshoe shape is probably due to the greater amounts of carbonate and shale that is present in the Saginaw Bay area. This unusual thickness of non-evaporite sediments could be from the proposed Georgian Inlet to the northeast of the southern peninsula of Michigan in Ontario, Canada (Briggs, 1958).

The A-2 Evaporite is generally present westward of the B-Evaporite and somewhat southward of it. The A-2 Evaporite wedges out very rapidly in the southwestern portion of the basin. Within ten miles the salt section thins from 250 to 0 feet.

Several large embayments can be observed. Of particular importance is the thickness of the evaporite section in the Chatham Sag area. In Oceana County there also is a noteworthy thickening of the evaporite section. There is an unusual thickening of the section in Barry County in the southwestern portion of the basin. This unusual thickening could be related to a yet unnamed sag somewhat west of Melhoun's (1958) proposed Battle Creek Trough. The Salina isopach (Map No. 3) and B-Evaporite isopach (Map No. 6), also notes a thickening of sediments in this area. Detailed, unpublished structure contour maps indicates a sag plunging southwest from Barry County through Kalamazoo and Cass Counties (Ells, personal communication). Gravity and magnetic geophysical data from the geophysical section of the Department of Geology, Michigan State University also support the existance of a narrow sag plunging southwest from Barry to Kalamazoo County (Dr. W. Hinze, personal communication). Several recent wells drilled in this area since the completion of the enclosed maps support the preceding statement.

The A-2 Evaporite thins very rapidly in the reef areas. This is noted on the map by the hachured areas. This very rapid thinning of the A-2 Evaporite over reef sections may be an aid to drillers in determining the presence of nearby reefs.

Discussion of the A-2 Carbonate. The A-2 Carbonate unit extends from the top of the A-2 Evaporite to the base of the B-Evaporite. This unit varies between 100 and 200 feet in thickness. From a study of the included cross sections it appears the A-2 Carbonate averages 120 feet thick in the northern two-thirds of the basin and closer to 200 feet in thickness in the southern one-third of the basin. In general the carbonate units tend to thicken as the A-2 and B-Evaporites thin out near the edges of the Michigan Evaporite Basin. This situation is not what would be expected in a large sedimentary basin. Within the area of salt deposition the A-2 Carbonate is mainly a limestone, but in many sections it is represented by a buff to brown dolomite or alternating beds of limestone and dolomite. The typical section in the basin is a 100 foot limestone section topped by a 20 foot dolomite. This can be distinctly noted on two of the included cross sections. The A-2 Carbonate can be split into an A-2 Limestone and an A-2 Dolomite. This differentiation of the A-2 Carbonate is noted on the Salina geologic column (Figure 4). The A-2 Limestone and A-2 dolomite are terms which have been used for a number of years on drillers logs. In places the A-2 Carbonate tends to be shaly or anhydritic. Some horizons of the A-2 Carbonate also split into the thin "poker chip" laminae similar to those noted in the A-1 Carbonate.

In the area south of the pinchout of the major evaporite units the A-2 Carbonate is generally a buff to brown, dense to crystalline dolomite. Cores from the Overisel field in Allegan County show that the A-2 Carbonate is locally fractured. These fractures in a number of cases were completely resealed with anhydrite (Ells, 1960). The A-2 Carbonate is an oil and gas producer, especially in southwestern Michigan in the dolomite section of the Southern Carbonate Shelf.

Discussion of the B-Evaporite. The B-Evaporite extends from the top of the A-2 Carbonate to the base of the C-unit. The top of the B-Evaporite section has been picked as the top of the first salt bed found below the C-unit. This pick is in line with the view that the B-Evaporite is a stratigraphic unit which was originally deposited during a time of fairly uniform environmental conditions.

The B-Evaporite averages between 200 and 300 feet in thickness within the salt section, but reaches a thickness of at least 440 feet near the center of the Michigan Basin. This unit is composed predominantly of salt, but there are often shale, dolomite, and anhydrite lenes interbedded in the section. This is especially true in the upper half of the section where shale and dolomite lenses reach a thickness of as much as 50 feet. Dolomite and shale impurities in some areas of the basin compose up to 25 per cent of the total B-Evaporite unit. In the norther portion of the basin a 10 to 20 foot anhydrite bed is often present close to the base of the B-Evaporite. This unit has slightly shifted toward the east of the A-1 and A-2 Evaporites.

Discussion of the B-Evaporite Isopach Map (Map No. 6). The B-Evaporite isopach map notes a definite embayment in the area of the Chatham Sag. Another significant embayment is noted in St. Clair County just south of the proposed Port Huron Monocline as observed on the B-Evaporite structure contour map. The B-Evaporite varies in thickness from 150 to 300 feet in the reef zone in St. Clair County. An embayment is also noted in the northern portion of the basin in

Cheboygan County.

The salt pinchout though indicated by a fairly smooth line is quite probably a very irregular feature. The pinchout was probably greatly influenced by minor structural features and the presence of reefs in the wedgeout area. The B-Evaporite rapidly pinches out parallel to the Howell Anticline. In Wayne County a drop from 250 feet to 0 is recorded within one township. It is also interesting to note the great irregularity of the isopach contours over the Howell Anticline where enough sample logs were available to give a somewhat detailed picture.

The trace of the evaporite pinchout indicates that the Michigan Evaporite Basin is far from the present geographic center of the southern peninsula of Michigan. The basin quite likely underlies a good portion of Lake Huron (Figure 3). Again the fact that major sections of salt have been recorded in the Salina formation of Ontario, Canada tends to confirm this statement (Caley, 1945).

Discussion of the structure contour map based on top of the B-Evaporite (Map No. 5). This map is very similar to that of the Niagaran and Salina structure contour maps. The center of the basin is located in central Gladwin County. The regional dip is fairly uniform over the Michigan Evaporite Basin though it is somewhat steeper in the north. The basin is ovate with almost an east-west lineation on this particular map.

The Howell Anticline is a very prominent feature, but the Freedom Anticline is obscured since the B-Evaporite wedges out in that area. The presence of a fault or series of faults along the southwestern flank of the Howell Anticline is extremely apparent.

An anticline or more possible a fault trend exists in the Sanilac County area. This feature is in the vicinity of the Port Huron Monocline and has a northwest-southeast trend which is sub-parallel to the Albion-Scipio oil field trend.

Discussion of the C-Unit. The C-Unit extends from the top of the B-Evaporite to the base of the D-Evaporite. This unit is composed primarily of dolomitic shale with minor amounts of anhydrite. In some sections it is represented by an argillaceous dolomite. It is often termed the C-Shale and a study of the three included cross sections prove this term valid. The C-Unit is present over all of the basin except where it has been eroded.

The C-Unit varies in thickness from about 140 feet near the center of the basin to 30 feet in the southern portions of the basin. The northern and eastern portions of the basin are a fairly consistent 100 feet of dolomitic shale. No oil or gas shows have been reported and the porosity of this unit is extremely poor.

Discussion of the D-Evaporite unit. The D-Evaporite is almost entirely composed of salt with some shale, dolomite, and anhydrite present in a few scattered sections. The average thickness of the D-Evaporite is 50 feet with the thickest section of 80 feet being observed in the central portion of the basin. In the southern portion of the basin this salt is usually about 30 feet thick and in some of the reef areas it is not present. A migrational trend of the lateral distribution of the sediments toward the northeast can again be noted.

The D-Evaporite unit is not considered in later discussions as a serious target for radioactive waste disposal due to its limited stratigraphic thickness and the presence of the often porous E-Unit above it.

Discussion of the E-Unit. The E-Unit extends from the top of the D-Evaporite to the base of the F-Unit. It is an argillaceous dolomite which does possess distinct 10 to 20 foot shale beds. In the western and southwestern areas of the Michigan Basin the E-Unit has been described as a crystalline dolomite which is very often porous and water-bearing. This porous zone in the E-Unit has been termed the "Kintigh" zone by drilling operators. This zone appears to be present over much of the southern one-third of the Michigan Basin (Ells, 1960). Oil and gas shows have been reported from this zone, and in Allegan County oil is produced in the Diamond Springs field (Ells, 1960). The "Kintigh" zone may become of increasing importance as an oil and gas pay zone in the coming years.

The thickness of the E-Unit in the area of salt deposition averages 120 feet with the thickest section of 170 feet being recorded in southern Shiawassee County. Information from deep tests near the center of the basin indicate that the E-Unit is slightly thicker than the 120 feet average.

Discussion of the F-Unit. The F-Unit is predominently a salt section with major shale and dolomite beds scattered through the section. Considerable anhydrite is disseminated throughout the section, especially in some of the shale units. It extends from the top of the E-Unit to the base of the G-Shale.

The thickness of the F-Unit varies irregularly from one county to another. The following general figures were computed for the F-Unit within the boundaries of the major evaporite section. The F-Unit varies from an average of 370 feet in the southern part of the basin to approximately 650 feet thick in the northern portion of the Michigan Evaporite Basin. In the center of the basin the F-Unit reaches a thickness of over 1000 feet.

The per cent of salt in the F-Unit varies considerably throughout the basin. It is generally from 30 to 50 per cent in the south and 60 to 70 per cent in the northeast. The number of distinct salt beds in the F-Unit varies from one to five and the thickness of the individual beds from 20 to 250 feet. Again a definite shift of the basin toward the northeast can be noted in the F-Unit.

Discussion of the G-Shale. The G-Shale unit extends from the top of F-Unit to the base of the Bass Island formation. It is composed mainly of a green to gray dolomitic shale. In random places in the basin the shale has a reddish color. Anhydrite is also commonly present, but not in major amounts.

The thickness of the G-Shale varies from 120 feet in the southeast to 40 feet nearer the center of the basin. In the north the average thickness is about 70 feet. A recent opinion of some geologists is that the G-Shale in the northern portion of the basin is actually composed of two shale units with a salt section separating them. In the western portion of the state the G-Shale is somewhat harder to distinguish for it is often quite dolomitic. It can normally be easily picked on radioactivity logs. The maximum thickness as noted on the inclosed cross section was 160 feet of shale and dolomitic shale in northern Oakland County. Since the G-Shale seems to be quite thick near the Chatham Sag and appears to thin somewhat toward the west and the center of the basin it is suggested that the calcarous mud was brought in through the Chatham Sag. Since the shale unit thickens slightly in the northern portion of the basin, it is probable that the fine mud came from the area of the Canadian Shield.

Discussion of the structure contour map based on the top of the Salina formation (Map No. 2). An attempt was made to pick the top of the G-Shale as the true top of the Salina formation when preparing the structure contour map on top of the Salina formation. In many of the older sample logs the Salina top had been picked as the top of the upper salt in the Silurian geologic column. The Salina shale is the first major shale unit above the upper salt in the Salina formation. In most areas this pick can be easily distinguished on a radioactivity log. The top of the Salina formation is much easier to distinguish than the top of the Niagaran formation. This is one reason the included cross sections use the Salina top as datum level.

The structure contour map on the top of the Salina formation indicates that the Michigan Basin is fairly symmetrical, but with a somewhat elongated northwest-southeast axis. The center of the basin is located in southwestern Gladwin County. The Howell, Freedom, and Deerfield Anticlines are prominent features. It is extremely evident from the steep southwestern slope of the Howell Anticline that major faults exist in this area. Several anticlinal noses can be observed in the Macomb-St. Clair County area. It is difficult to say if these are true anticlines or only a reflection of the reef masses beneath the Salina evaporites. It is possible that they are anticlinal trends which have been accentuated by the reef buildups. Several prominent highs can be observed in southern Kent and northwest Allegan Counties. These are due mainly to structures in the Salina formation since they are not prominent on the structure contour map at the base of the Salina formation. Though structurally the Chatham Sag is not very apparent, there does seem to be a definite low in the Clinton Sag area. This effect might have been increased by faulting on the southwestern side of the Freedom Anticline or by the erosion of upper Silurian sediments in this area. Two major lows can be noted in Mason and Oceana Counties.

Structural features appear to control the thinning of the salt units in the Salina formation to a limited extent. Examination of the isopach maps of the A-2 and B-Evaporites indicate this especially in the area of the Howell Anticline. This could be considered evidence that this structural feature was present in at least early Salina time though not as a very prominent feature. The Howell Anticline is not believed to have been formed as it is noted today before middle Mississippian time (Kilbourne, 1947). Kilbourne also noted that the Howell Anticline was probably associated with a weakness or fracture in the basement rock. The orientation of the evaporite basin's hingeline nearly parallel to the Howell structure indicates that there might have been a slightly positive region present here at various times during the Silurian.

It is interesting to observe the steepness of the regional dip in the northwestern portion of the basin. Though the hingeline of the Michigan Evaporite Basin can not easily be distinguished, a general leveling of the regional dip is noticeable in the area of the Southern Carbonate Shelf.

Discussion of the Bass Island Dolomite or H-Unit. The Bass Island Group is directly above the Salina formation within the Michigan Evaporite Basin. The Bass Island group is composed predominetly of dolomite with several thin anhydrite horizons appearing in random places in the basin. Near the center of the basin, shaly lenses have been noted. The color of the Bass Island Dolomite varies from a light cream to buff on the margins of the evaporite basin, to a darker brown near the center of the basin. The thickness of this unit varies from 100 feet near the margins of the evaporite deposition to about 600 feet near the center of the basin.

The close of Bass Island time is marked by a wide-spread disconformity which corresponds to the general unwarp of the Silurian throughout the midwest. This disconformity is not readily recognized near the center of the basin and its existance there is doubted by a number of geologists. As one proceeds outward from the center of the Michigan Basin one Silurian unit after another is truncated (Ells, 1958). This is especially noteworthy in the area of the Southern Carbonate Shelf. Since the disconformity does not truncate any of the Salina evaporite members it was not studied in detail.

RADIOACTIVE WASTE DISPOSAL CONSIDERATIONS

Properties of Salt Bodies for Waste Disposal

The United State Atomic Energy Commission has considered the possibilities of underground radioactive waste disposal in subsurface rock formation. Those formations containing stagnant brines and solution caverns in salt beds or salt domes have been of special interest. The possibilities of storing the waste in underground excavations such as in impermeable shales has also been considered (Deutsch, 1960).

There are several apparent advantages which make salt units more desirable then other types of rock storage containers.

1. The cavity which is to contain the radioactive waste can be produced by standard saltbrine well techniques. The salt would be dissolved in the cavity by pumping fresh water into the salt unit and then removing the saturated solution. This technique eliminates the need for an expensive mine shaft which could also be difficult be seal.
2. Salt units have a tendency to seal off possible avenues of radioactive waste escape along faults. Salt under

pressure is believed to flow somewhat thereby sealing any porous zones in the rock.

3. Upon completion of the cavity the salt will form a fairly hard, impermable crust on the interior of the sealed cavity.

Discussion of Radioactive Waste Disposal Areas

Several formations in the Michigan Evaporite Basin have been suggested as possible areas which would be suitable for the disposal of high-level, semi-liquid, radioactive wastes (Joseph, 1955). These formations possess various amounts of connate waters or brines which are believed to migrate at rates not in excess of several feet per year (Deutsch, 1960). The Salina formation has been selected as one of the most desirable formations in which waste could be economically stored. The Salina formation is at least 1000 feet below the surface where-ever the salt sections are developed. Since there are several major evaporite units in the Salina formation, it offers an unusual opportunity for the development of radioactive waste disposal sites.

Problems of Radioactive Wast Disposal

Upon the detailed examination of any particular rock unit there are many problems which make the exact site selection extremely complicated. These problems have been divided into three major classes; cultural problems, engineering problems, and geologic problems.

Cultural problems. One of the major cultural problems is the education of the public on the dangers or lack of dangers which a radioactive waste disposal site might possess. Though safety devices would eliminate any danger to nearby residents it would still seem advisable to place the site in a relatively unpopulated area. Other cultural problems would be the relationship of the site to the various methods of transportation and also its relationship to potential sources of radioactive waste.

Engineering problems. One of the possible engineering or chemical problems which would have to be studied would be the effect of the radioactive waste on the rock surrounding the underground disposal area. This would include the chemical and heat effects on the surrounding rock. The fact that radioactive wastes often give off a significant amount of heat could indeed be a major complication. Heat combined with the highly corrosive nature of the waste could possibly produced unusual chemical effects (Gorman, 1955). Another problem presently being considered by members of the civil engineering department at Michigan State University is the possible flow of evaporites under differential stress.

Geologic problems. The third and major class is that of geological problems which would effect the selection of an underground radioactive waste disposal site. This class can be broken into several subclasses.

The first subclass which has been considered is that of structural problems which could effect the selection of a waste disposal site. Any area which has been subjected to fairly extreme folding would be considered a questionable area to place such a site. Such areas of folding as the Freedom Anticline, Port Huron Monocline, and the Howell Anticline would be important examples. Not only are structural anomalies potential oil and gas provinces, but they are also areas in which larger faults could be expected to be concentrated.

The major faults in Michigan, which generally have a northwest-southeast trend, would definitely be areas which would represent poor risks for radioactive waste disposal sites. These faults could act as potential avenues of escape for the semi-liquid radioactive waste to important aquifers above the Salina formation. Examples would be the Albion-Scipio trend and the apparent series of faults concentrated in the Freedom-Howell Anticline areas. Polution of possible aquifers should be recognized as one of the most definite dangers of underground waste disposal. Since in the case of the Albion-Scipio trend, important oil and gas reserves could be contaminated, this would be another reason to avoid areas of known faulting.

One feature which can be considered a secondary structural feature is Landes's proposed collapse area in southeastern Macomb County. This feature is noted on several of the maps accompanying this paper. During the discussion of the Salina isopach map, it was noted that new evidence indicates non-deposition or possibly slow removal causing the sediments to subside without losing their identity (Ells, personal communication). It is noteworthy that the salt units are very inconsistent to the east of this unusual area in Canada as the proposed evaporite pinchout is approached (Caley, 1945).

An area where leaching could well be significant is in southern Wayne County where an abrupt thinning of the B and F salts can be noted. Landes presented the following evidence for collapse after leaching in this area (Landes, 1945).

1. The abrupt termination of the salt north of Trenton, Michigan.

2. Differences in the structure below and above the salt series where the B and F salts wedgeout.

3. The presence of small faults, abnormal and variable dips, and breccia of probable collapse origin in the outcroping bedrock in this area.

The abrupt pinchout of these salts coincides roughtly with the Howell Anticline.

Possible areas of leaching appear to exist all along the zone of pinchout of the salt units. Most of the leaching was probably on a small scale and was caused by the influx of very small amounts of meteric waters from the associated low land masses at or near the original time of deposition of the evaporites.

The second subclass of geologic limitations on the selection of a radioactive waste disposal site may be considered of a generally stratigraphic nature. These are problems which are closely related with the environment of deposition of the original sediments.

To gain a complete stratigraphic picture, a detailed knowledge of the lateral and vertical extent of the major evaporites in the Salina formation is required. To complete the picture, the study has to be expanded to include those members of the Salina formation which lie above and below the major evaporite units. Based on this work the following questions are selected as essential in establishing the criteria for the selection of an exact radioactive waste disposal site.

1. Are there porosity zones present in the particular salt which is to contain the radioactive waste?
2. Are there any unusual minerals present which could be affected by the corrosive nature of the radioactive waste?
3. Is the salt unit being considered of a consistent thickness over a large lateral area?
4. Are there major dolomite or shale stringers scattered through the salt section?
5. Are there porosity zones in the rock units above and below the selected salt unit?
6. Is the general area of the site near the salt pinchout where leaching and collapse are more probable?
7. Are there minor angular unconformities or thin conglomerate beds in the salt section?
8. Are there more than one section which could be used in case the primary salt section is found to be

unsatisfactory?

9. Is the salt section of sufficient vertical thickness to contain the desired volume of waste?
10. Are reef sections suspected to exist in the column in the selected area?
11. Is there a thick section of glacial drift in the proposed region of the site?

Most of the above questions can be answered for a select area by a study of the inclosed cross sections and maps.

The third subclass of geologic problems which might interfere with the selection of a particular disposal site is that of possible interference with reserves of economic minerals. For example it would be reasonable to isolate the disposal sites from possible future petroleum provinces. This would not only influence the Salina formation pay zones, but any deep tests that had to pass through the Salina formation. It is very difficult to accurately predict future oil fields from a regional study of this type. A good general rule would be to avoid the previously discussed structural features which indicate rapid reversals in dip. To avoid possible stratigraphic oil fields, such as the reef zone, it would be wise to stay at least thirty miles basinward from the hingeline of the Michigan Evaporite Basin. These principles would also largely avoid any chance of interfering with future gas storage facilities or future uses of the salt sections by the chemical industry.

Discussion of the Composite Geologic Map (Map No. 7)

The previously mentioned principles have been adhered to in the creation of a composite map of the Michigan Basin. This map does not point out specific areas which should be selected as possible radioactive waste disposal sites, but does point out those areas where geologic problems would discourage their selection. This composite map of geologic features notes the major structural trends which are believed to have been important during the deposition of the Salina formation. This map notes the areas around the evaporite basin in which reefs are known to exist or could possibly exist. The exact line as noted on the map is based on the relationship of the known structural features as determined from the total series of maps. Therefore the Composite Map of Geologic Features (Map No. 7), is the general summation of information gathered in this paper which is pertinent to the selection of a radioactive waste disposal site.

The A-2 Evaporite As A Radioactive Waste Disposal Target

The A-2 Evaporite has many of the characteristics which would make it an excellent radioactive waste disposal target. The following is a list of advantages of the A-2 Evaporite as a waste disposal target.

1. The A-2 Evaporite is a very chemically uniform salt across much of the Michigan Basin both laterally and vertically.
2. The 200-450 feet of vertical thickness should be ample for protection from possible migration of the semi-liquid waste by normal means of migration.
3. The A-2 Evaporite's great lateral extent makes the selection of an exact site less difficult.
4. Its stratigraphic position between the A-1 and B-Evaporite adds a degree of safety if waste were to migrate up or down a fracture zone.
5. The depth to the A-2 Evaporite varies between 2,000 and 7,000 feet depending upon the position of the site in relation to the center of the Michigan Basin.

Disadvantages of the A-2 Evaporite as a radioactive waste disposal target.

1. The A-2 Evaporite is situated between two potential oil and gas pays. The upper portions of the A-1

Carbonate often possess shows of oil and gas.

2. The A-2 Evaporite thins to less than 10 feet over the reef zones. Reefs have been found at least 30 miles from the salt pinchout toward the center of the basin. This would significantly limit the lateral extent over which the A-2 Evaporite could be selected as a waste disposal target.

3. Less information is available on the A-2 Evaporite than on the upper salt units. This is especially true in Kent and Wayne Counties.

The B-Evaporite as a Radioactive Waste Disposal Target. The following is a list of advantages of the B-Evaporite as a radioactive waste disposal target.

1. The B-Evaporite has a vertical thickness of several hundred feet with intervals of as much as 100 feet of clear salt.

2. The B-Evaporite has a wide lateral extent similar to that of the A-2 Evaporite.

3. The B-Evaporite though it thins slightly over reef zones is usually at least 250 feet thick over the crest of the reefs.

4. The C-Shale which is directly above the B-Evaporite generally acts as a good seal against possible migration

of radioactive wastes into good aquifers occuring higher in the column.

5. Though not as chemically uniform as the A-2 Evaporite, it is composed of a fairly consistent lithology over much of its lateral extent.
6. The B-Evaporite is located at a depth of between 1500 and 6500 feet below ground level.

Disadvantages of the B-Evaporite as a radioactive waste disposal target.

1. The B-Evaporite contains a greater number of dolomite, shale, and anhydrite lenses than does the A-2 Evaporite.
2. The A-2 Dolomite horizon of the A-2 Carbonate is at the base of the B-Evaporite. This horizon is often porous and is an oil and gas pay.
3. The B-Evaporite is commercially used for gas storage and is also a source of commercial salt in southeastern Michigan.

POSSIBLE ECONOMIC APPLICATIONS OF THIS STUDY

The Oil and Gas Industry

The Salina formation in the past several years has become an increasingly important rock unit to the Michigan petroleum industry. The large number of bioherms which apparently surround the Michigan Evaporite Basin have, in a number of locations, proved important sources of oil and gas. The reef production is presently concentrated in southeastern Michigan in Macomb and St. Clair Counties. A recent field in Jackson County and abnormal thinning of the A-2 Evaporite unit in other areas indicate that a considerable number of reefs will be found in the future. A general principle which has been noted from a study of the isopach map of the A-2 Evaporite indicates that these reefs will be primarily located within 30 miles of the salt pinchout.

The "Kintigh" porosity zone which is present in the E-Unit of the Salina formation may also become an important pay zone. This horizon has been recognized as possessing good porosity and oil shows over much of the Southern Carbonate Shelf area (Ells, Unpublished Maps). The "Kintigh" zone is generally from 5 to 10 feet thick and can be easily noted on radioactivity logs. In the last several years the

A-1 and A-2 Carbonate pay zones have become of increased interest to the petroleum industry.

The Port Huron Monocline or fault could well represent a situation similar to that of the Albion-Scipio trend. More drilling in this area should prove extremely interesting.

Another recent important economic use of the salt beds in the Salina formation is that of gas storage in southern Kent County, western Ottawa County, and along the crest of the Howell Anticline; LPG storage areas have been developed in the Salina evaporite units. With the growth of population in southern Michigan, it can be expected that gas storage facilities in the Salina formation will be expanded in the future.

The Salt Industry

The Salina evaporite units have for many years been a source of salt brines in southeastern Michigan. Rock salt is mined by conventional underground methods in southern Wayne County. The salt in these two areas is extremely important to the rapidly expanding chemical industry.

There is a possibility that some of the valuable rare salts which are found in extremely restricted conditions might be found in small basins that have been partially isolated from the much larger Michigan Evaporite Basin. This would suggest that the rare salts would be expected within the reef zone near the hingeline of the evaporite basin. This hypothesis has been deductively derived from Scruton's theory of evaporite deposition (Scruton, 1953).

SUMMARY AND CONCLUSIONS

The importance of the Salina formation as a source of economic minerals in the years to come should now be quite apparent. As a source of oil, gas, common salt, and possibly the rare salts; the presence of the Salina formation should represent a major stimuli to the growth of industry in Michigan. The use of the Salina formation for gas and radioactive waste storage should also become more significant. A means of disposal of radioactive waste can be of great assistance to the State of Michigan in competing with other geographic areas for nuclear power developments.

From a geological standpoint several conclusions have been highlighted by the analysis of the various regional maps and other sources of information gathered for this study. These have been separated into several categories for continuity of thought.

<u>Theoretical relationships</u>.

1. The Michigan Evaporite Sea of Salina time closely resembles those conditions which have been proposed for a theoretical evaporite basin.
2. Scruton's theoretical sequence of deposition as

predicted from experiment on the evaporation of sea-water is closely related to the sequence noted in the Salina formation. First a carbonate is deposited, followed by an anhydrite, then halite with anhydrite and at last nearly pure halite (Scruton, 1953).

Structural relationships.

1. The majority of the structural features in the Michigan Basin have a northwest-southeast orientation.
2. The Howell and Freedom Anticlines were present during the upper Silurian, but as much subdued structures when compared with their prominence during the Mississippian.
3. Much of the local structure in the Salina formation is due to the reef sections in the Guelph or "Brown Niagaran" horizon.
4. The regional dip in the northwestern portion of the basin is steeper than in other portions of the Michigan Basin.

Stratigraphic relationships.

1. There is excellent evidence for the elevation of the Salina formation to group level.
2. The Salina formation can be readily segregated into ten distinct members which can be traced across most

of the Michigan Basin.

3. The thickening of the Salina formation toward the center of the basin is due mainly to the sudden thickening of the evaporite sections. The carbonate units are fairly constant in thickness across the Michigan Basin.

4. The salt units generally grade into a thin anhydrite near the hingeline of the basin and then into a carbonate in the shelf region.

5. The hingeline of the Michigan Basin can be considered as the zone of pinchout of the Salina salt units.

6. The Michigan Evaporite Basin continuely shifted toward the east and northeast throughout Salina time.

Environmental relationships.

1. The Michigan Basin during Salina time appears to have a northwest-southeast orientation, but when the unexplored region under Lake Huron is considered the basin is quite probably ovate.

2. The depth of the Michigan Sea was generally under 50 feet. The average depth was probably between 10 and 30 feet. Large brine marshes and salt flats could have existed at random locations across the Michigan Evaporite Basin.

3. The Chatham Sag was a major source of seawater to the Michigan Evaporite Sea during Salina time.

4. Salt was deposited in the Michigan Evaporite Basin due to the high rate of evaporation and isolation of the basin from surrounding seaways.

5. The average temperature during the intervals of Salina salt deposition was equal to or greater than that found in the deserts of southwestern United States at present.

Economic relationships.

1. The "Kintigh" zone, the "Brown Niagaran" horizon, and portions of the A-1 and A-2 Carbonates are potential oil and gas pays.

2. The erratic thinning of the A-1 and A-2 Evaporites often indicates the close proximity of Guelph-Lockport reefs which can be excellent oil and gas reservoirs.

3. An important possibility exists that some of the rare salts will be found in restricted arms of the Michigan Evaporite Basin.

Radioactive waste disposal relationships.

1. A large lateral area exists in Michigan in which a radioactive waste disposal site could be established.

2. The A-2 and B-Evaporites appear to be the best suited targets for the disposal of radioactive wastes. The A-1 Evaporite might also prove to be an excellent target.

Several techniques were not explored in this study which could well add many missing details. The production of a structure contour map on one of the formations higher in the geologic column such as the Dundee Limestone could well point out some of the obscure geologic features of the Salina formation. This would be especially true near the center of the basin where information on the Salina formation is very limited. Since more information is available on the Dundee formation, its structure might reflect the deeper Salina structure to some extent. The construction of an isopach map of the A-1 Evaporite could add important detail to the reef complex and information on the significance of the shifting of the center of the basin during early Salina time. A more detailed study of the F-Unit would also add valuable information on lateral shift of the basin. As more information becomes available, the production of these maps should become of more importance.

An attempt has been made to combine all of the scattered sources of information on the Salina formation. This has been done to present a consolidated picture of the geography and environment existing during Salina time. From this study it is desired that the interests of a greater number of people might be aroused on the importance of the Salina formation to the economic future of the State of Michigan.

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APPENDIX

APPENDIX

The information contained in this appendix was largely obtained from 358 sample logs which are on file at the Michigan Geological Survey, Lansing, Michigan. In a number of cases the tops of the various units, as picked by the Michigan Geological Survey, were in disagreement with those of my own. This was generally only the case in those deep tests which were described before 1950. The various unit tops were used to produce the included maps. The location of the wells are given in accordance with the Michigan township-range grid system as portrayed on The Index of Well Locations Map (Map No. 8). The location of the wells are accurate to the nearest section. The elevations are in relationship to sea level.

Several symbols have been used in this appendix which demand explanation.

---- Information not available.

NP Unit not present.

PO Pinchout.

No.	Location	Elevation	Permit No.	Salina Top	Niagaran Top	B-Evaporite Top	A-2 Evaporite Top
1.	31-35N-6E	669	20194	1110	2526	2081	----
2.	20-34N-6E	833	22638	1620	3375	----	----
3.	5-34N-2E	830	-----	1550	2970	2545	----
4.	18-34N-1W	842	21198	1485	2968	2553	----
5.	1-34N-2W	862	20879	1435	2830	2574	----
6.	9-34N-2W	909	19422	2149	3331?	----	----
7.	8-33N-8E	600	-----	1260	----	----	----
8.	3-33N-1E	881	19126	1906	3680	3068	3510
9.	18-32N-6E	803	2960	2035	4030	3084	3467
10.	24-32N-5W	964	19114	2774	4175	3808	----
11.	19-32N-8W	868	22639	2540	3831	3480	3780
12.	6-30N-11W	913	22627	2632	3850	3511	3806
13.	10-29N-2W	1254	17455	4420	6658	5609	5986
14.	15-29N-2W	1244	16902	4445	6670	5600	5990
15.	16-29N-2W	1253	17763	4491	6644	----	----
16.	5-29N-12W	1004	10103	2878	4095	----	----
17.	25-26N-12W	976	18566	4102	5709	5034	5526
18.	9-25N-10W	1109	18512	4702	6741	5710	6201
19.	23-24N-1W	1192	21409	5361	----	----	----
20.	35-24N-15W	776	17709	3187	4539	3959	----
21.	35-22N-2E	903	12898	5393	8547	7126	7667
22.	14-22N-14W	843	18697	4119	5796	4804	5179
23.	12-21N-17W	591	14	2795	4195	3309	3680
24.	24-21N-17W	619	21499	2830	4140	3311	----
25.	20-19N-17W	690	18002	3138	4479	3589	3948
26.	30-19N-17W	691	22738	3321	4525	----	3975
27.	22-19N-18W	647	17783	3010	4307	3416	3770

No.	Location	Elevation	Permit No.	Salina Top	Niagaran Top	B-Evaporite Top	A-2 Evaporite Top
28.	26-19N-18W	640	17784	3020	4313	3429	3785
29.	27-19N-18W	628	17755	3002	4278	3347	3744
30.	27-19N-18W	641	20118	3001	4279	3375	3765
31.	29-18N-10W	1133	12802	5251	7342	6100	6556
32.	22-17N-15E	624	11834	3432	5505	4440	----
33.	25-17N-16W	723	987	3428	4825	3940	4217
34.	18-17N-17W	702	967	----	----	3442	3769
35.	2-17N-18W	850	18665	3256?	4556	3582	3964
36.	10-16N-15E	675	5045	3655?	----	----	----
37.	16-16N-16W	876	12194	3325	----	3800	----
38.	6-16N-17W	648	17549	2912	4241	3263	3606
39.	31-15N-16E	661	11738	3101	5086	4017	4463
40.	34-15N-4E	613	10551	5510	----	6845	----
41.	2-14N-4E	599	5441	5480	8270	6820	7330
42.	10-14N-17W	926	13657	3485	----	3486	----
43.	13-14N-17W	837	18031	----	4480	3465	3832
44.	33-14N-17W	768	631	3179	4045	3205	3500
45.	8-14N-18W	835	16145	2797	----	3117	----
46.	21-14N-18W	704	11936	2840	----	2940	----
47.	12-13N-13W	830	411	3960	5550	4410	4815
48.	14-13N-18W	707	12877	3161	----	3380?	3563
49.	11-12N-13W	822	13816	3702	5155	4475	4904
50.	26-12N-14W	749	22849	3317	4700	3720	4050
51.	30-12N-17W	648	-----	2915	3601	NP	3099
52.	30-12N-17W	642	17058	3000	3790	NP	3097
53.	12-12N-18W	680	18540	----	3657	2946	3127
54.	12-12N-18W	664	18606	----	3633	2948	3118

No.	Location	Eleva-tion	Permit No.	Salina Top	Niagaran Top	B-Evapor-ite Top	A-2 Evapor-ite Top
55.	7-11N-14E	797	22857	3710	5700?	3835	5128
56.	12-11N-13W	883	788	3965	5124	4035	4425
57.	35-10N-16E	746	18308	2485	4148	3233	3710
58.	15-10N-15E	761	11405	2789	4640	3602	4057
59.	5-10N-9E	873	20209	4487	6856	5569	6087
60.	31-10N-10W	856	63	4080	----	4150	----
61.	8-10N-16W	636	309	2885	3600	----	3080
62.	24-9N -15E	752	2292	2396	----	3238	----
63.	26-9N -15E	751	10918	2430	----	----	----
64.	32-9N -12W	903	18027	----	4570	3594	3920
65.	6-9N -13W	704	537	3238	4295	3352	3656
66.	13-8N -16E	629	12035	2015?	----	2780	----
67.	27-8N -16E	728	1395	----	3790	2883	3335
68.	20-8N -13E	794	18561	2953	4845	3847	4355
69.	27-8N -4W	747	19272	4122	5848	4762?	5151
70.	10-8N -4W	737	336	3161	4237?	3250	3527
71.	18-7N -17E	653	22698	1776	3430	2606	----
72.	15-7N -16E	740	17862	1950	3630	2744	----
73.	31-7N -16E	697	19556	1810	3434	2767	3074
74.	14-7N -11E	901	17786	3222	5025	4010	----
75.	35-7N -9W	678	3090	3185	4536	3513	3918
76.	25-7N -15W	628	21002	2622	3442	NP	NP
77.	27-7N -16W	613	410	2515	3125	NP	NP
78.	36-7N -16W	634	5689	2362	3180	NP	NP
79.	9-6N -17E	609	11001	1585	3020	2240	----
80.	29-6N -17E	602	-----	1367	----	2029	2475

No.	Location	Elevation	Permit No.	Salina Top	Niagaran Top	B-Evaporite Top	A-2 Evaporite Top
81.	19-6N -16E	650	22668	1672	3140	2408	2818
82.	11-6N -15E	698	15355	1980	3429	2612	3073
83.	12-6N -15E	675	19876	1757	3302	2478	2931
84.	13-6N -15E	673	21264	1750	3260	----	2922
85.	33-6N -13E	809	22198	2393	3806?	3000	2518
86.	18-6N -12E	906	22534	2782	4514	3680	4048
87.	25-6N -11E	941	12933	2700	----	----	----
88.	12-6N -9W	636	16734	3415	----	3430	3575
89.	5-6N -13W	714	22355	2868	----	----	----
90.	31-6N -15W	632	21020	2586	3090	NP	NP
91.	15-5N -16E	620	19872	1643	2872	2078	2588
92.	28-5N -16E	627	18522	1585	2729	2036	2509
93.	9-5N -15E	704	21544	1875	3237	2472	2919
94.	14-5N -15E	655	21353	1697	3119	2317	2797
95.	20-5N -15E	696	21847	1789	3190	2427	2853
96.	25-5N -15E	640	22036	1666	2917	2140	2616
97.	31-5N -15E	709	22060	1708	3120	2348	2818
98.	35-5N -15E	658	17927	----	2940?	2160	2635
99.	27-5N -14E	768	22708	1875	3276	2530	2948
100.	29-5N -14E	708	21878	1922	3305	2536	3005
101.	7-5N -13E	785	22439	2252	3810	2964	3647
102.	14-5N -11E	1028	22611	2695	4285	3452	3916
103.	9-5N -13E	789	22471	2245	----	----	3414
104.	36-5N -12E	757	19511	2056	3655	3790	3270
105.	5-5N -2E	856	22379	3198	3957	3900	4412
106.	23-5N -2E	913	16738	3080	4733	3824	4276

No.	Location	Elevation	Permit No.	Salina Top	Niagaran Top	B-Evaporite Top	A-2 Evaporite Top
107.	14-5N-3W	828	8274	3700	5199	4145	4626
108.	3-5N-9W	820	17535	3391	----	3411	----
109.	3-5N-9W	822	21780	3372	----	3703	3372
110.	21-5N-10W	758	11540	2740	3820	3015	3278
111.	21-5N-10W	782	-----	2710	3856	3027	----
112.	17-5N-11W	761	20993	2753	3261	NP	3277
113.	23-5N-13W	872	20874	2752	----	NP	NP
114.	34-5N-13W	768	21289	2620	----	NP	NP
115.	11-5N-14W	712	20949	2573	3375	NP	NP
116.	29-5N-14W	605	20944	2290	3039	NP	NP
117.	32-5N-14W	619	21077	2315	----	NP	NP
118.	9-8N-14W	695	22852	2744	3950	3071	----
119.	11-5N-15W	649	21529	2452	3180	NP	----
120.	34-5N-15W	675	21724	2311	3000	NP	NP
121.	6-4N-16E	614	-----	1485	2585	1860	----
122.	19-4N-17E	594	21575	1483	2470	1766	2179
123.	1-4N-16E	589	9271	1485	2578	1853	2335
124.	3-4N-16E	630	48	1500	2745	2095	----
125.	5-4N-16E	636	21639	1592	2746	----	2474
126.	16-4N-16E	622	20814	1440	2635	1965	2393
127.	26-9N-16E	593	20989	1440	2436	1815	----
128.	13-4N-15E	634	21276	1527	2665	2060	2450
129.	22-4N-15E	643	21207	1568	2550	2003	2475
130.	22-4N-15E	647	21266	1594	2694	1980	2476
131.	22-4N-15E	647	20551	1540	2617	2024	----
132.	31-4N-15E	614	20412	1570 ?	2689	1957	2430

No.	Location	Elevation	Permit No.	Salina Top	Niagaran Top	B-Evaporite Top	A-2 Evaporite Top
133.	32-4N-15E	616	21570	1595?	2590	2209	2652
134.	17-4N-14E	660	21971	1727	3132	2365	2798
135.	22-4N-14E	653	21583	1727	2960	2184	2644
136.	1-4N-13E	680	21892	1845	3256	2493	3038
137.	11-4N-11E	948	19633	2380	3951	3118	3553
138.	29-4N-11E	983	21706	2435	3910	3588	3182
139.	14-4N-8E	1039	8450	2905?	4639	3677	----
140.	22-4N-8E	1024	12072	2805	2618	3668	4169
141.	9-4N-7E	1004	22665	3080	4916	3862	4456
142.	16-4N-3E	912	19849	2653	4398	3375	3980
143.	28-4N-3E	900	22642	2824	4167	----	3882
144.	36-4N-3E	932	11737	2230	3940	----	3585
145.	2-4N-11W	840	21779	2926	----	NP	----
146.	22-4N-11W	860	20937	2865	3608	NP	NP
147.	29-4N-12W	788	5030	2530	3279	NP	NP
148.	20-4N-13W	691	19691	----	3080	NP	NP
149.	9-4N-14W	661	21489	2275	----	----	----
150.	22-4N-14W	654	20379	2225	2972	NP	NP
151.	2-3N-16E	594	21007	1288	2396	1681	2134
152.	6-3N-16E	626	21848	1394	2451	2289	1849
153.	8-3N-16E	604	20896	1330	2440?	1731	2126
154.	15-3N-16E	599	20093	1330	2320	1660	2094
155.	31-3N-16E	581	19632	1334	2350	1653	2107
156.	1-3N-15E	627	21806	1390	----	1765	----
157.	1-3N-15E	618	19726	1420	2500	1853	2249
158.	2-3N-15E	621	17778	1490	2511	1900	2319
159.	11-3N-15E	608	21094	1454	2470	2279	1844

No.	Location	Elevation	Permit No.	Salina Top	Niagaran Top	B-Evaporite Top	A-2 Evaporite Top
160.	15-3N-14E	593	22511	1440?	2650	2362	2034
161.	28-3N-14E	582	21841	1519	2550	1935	----
162.	29-3N-14E	592	1359	1930	2402	2140	2344
163.	28-3N-13E	603	17605	2204	2792	2578?	----
164.	35-3N-13E	597	-----	----	2500	1944	2450
165.	36-3N-13E	629	19898	1736	2682	2046	2496
166.	28-3N-5E	993	22853	2574	4170	3344	----
167.	6-3N-4E	938	15561	2431	4121	3355	3800
168.	7-3N-4E	910	19446	2224	3923	3184	----
169.	34-3N-4E	912	13877	2350	3912	3210	3645
170.	35-3N-4E	914	2179	2340	3970	3157	3676
171.	36-3N-3E	905	19063	----	4507	----	----
172.	14-3N-1E	908	10011	3566	4764	4025	4495
173.	4-3N-9W	816	18526	2800?	3708	----	3195
174.	8-3N-9W	796	7873	2638?	3642	2945	3172
175.	17-3N-11W	833	22622	2611	----	NP	NP
176.	25-3N-11W	773	20917	2648	3286	NP	NP
177.	3-3N-12W	712	21189	2406	----	NP	NP
178.	4-3N-12W	717	21103	2452	3155	NP	NP
179.	18-3N-12W	736	20184	2330	3066	NP	NP
180.	22-3N-13W	854	21039	2436	3070	NP	NP
181.	1-3N-14W	654	20570	2202	3878	NP	NP
182.	9-3N-15W	718	22809	2233	2831	NP	NP
183.	28-3N-15W	712	22899	2149	2693	NP	NP
184.	8-2N-16E	577	1083	1225	2120	2120	----
185.	25-2N-7E	956	18766	2000	3668	3124	----

No.	Location	Elevation	Permit No.	Salina Top	Niagaran Top	B-Evaporite Top	A-2 Evaporite Top
186.	35-2N-7E	978	21298	1982	3850	3142	----
187.	13-2N-5E	1000	15389	2505	----	3355	3915
188.	7-2N-5E	938	13105	2550	3915	3140	3670
189.	34-2N-5E	940	1344	2600	4060	2795	----
190.	1-2N-4E	949	13518	2370	3886	3200	3645
191.	18-2N-5W	923	22672	2832	3935	----	----
192.	34-2N-9W	974	20732	2486	3434	2825	3082
193.	33-2N-10W	923	20875	2594	----	NP	NP
194.	9-2N-12W	834	21044	2525	3120	NP	NP
195.	21-1N-11E	678	-----	1410 ?	----	2115	----
196.	32-1N-8E	962	18762	----	3514 ?	2852	3300
197.	32-1N-8E	962	19090	1864	3457	2830	3286
198.	30-1N-7E	921	18967	2149	3604	2945	3368
199.	21-1N-7E	939	7227	1990 ?	----	2945	3490
200.	28-1N-7E	973	19506	----	3637	2938	3385
201.	35-1N-7E	1021	19097	1860	3568	2800	3317
202.	35-1N-7E	1020	19055	1835	3574	2850	3353
203.	6-1N-6E	926	15875	2205	3841	3150	3590
204.	9-1N-6E	907	17719	2115	3779	3035	3560
205.	12-1N-6E	928	19052	2059	3780	3100	3540
206.	33-1N-3E	910	16636	2270 ?	3395	2876	2915
207.	13-1N-2E	971	22607	2550	3497	----	----
208.	18-1N-5W	900	21769	2760	3620	3130	3330
209.	17-1N-6W	956	22541	2644	3488	----	----
210.	28-1N-6W	864	429	2585	3410	----	3230

No.	Location	Elevation	Permit No.	Salina Top	Niagaran Top	B-Evaporite Top	A-2 Evaporite Top
211.	3-1N-12W	760	22646	2284	2900	NP	NP
212.	29-1N-15W	662	15327	1735	2293	NP	NP
213.	13-1S-11E	633	-----	1040	2395	1830	----
214.	8-1S-8E	861	19241	1625	3180	----	2911
215.	9-1S-8E	860	19665	----	3225	2492	3059
216.	18-1S-8E	860	19329	1550	3040	2372	2817
217.	21-1S-8E	879	19541	1500	3000	2353	----
218.	8-1S-7E	945	19499	2164	3570	2849	3349
219.	16-1S-7E	915	10141	1917?	3379	2726	3250
220.	12-1S-7E	937	19254	1672	3233	2515	2985
221.	27-1S-7E	886	10792	1795	3244	2565	3037
222.	33-1S-5E	951	19371	2310	3142	NP	----
223.	7-1S-3E	936	21024	2346	2986	NP	NP
224.	11-1S-3W	937	21842	2678	3582	3066	NP
225.	12-1S-5W	992	21517	2620	3181	NP	NP
226.	16-1S-5W	999	21772	2552	3371	NP	NP
227.	24-1S-5W	934	21627	2550	3330	NP	NP
228.	27-1S-10W	916	20572	2138	2720	NP	NP
229.	15-1S-12W	782	-----	1998	2643	NP	NP
230.	32-1S-12W	789	-----	1894?	2527	NP	NP
231.	26-1S-16W	650	6352	1516	2050	NP	NP
232.	29-2S-11E	586	20696	840	----	----	----
233.	35-2S-11E	577	-----	1998	2643	NP	NP
234.	22-2S-10E	612	-----	955	2240	1600	----
235.	6-2S-8E	821	2961	1590?	2952	2275	----
236.	25-2S-8E	658	3813	875	2425	1775	----
237.	12-2S-7E	818	1134	1648	2960	2320	2790

No.	Location	Elevation	Permit No.	Salina Top	Niagaran Top	B-Evaporite Top	A-2 Evaporite Top
238.	32-2S-7E	788	3828	1717	2651	2175	PO
239.	28-2S-5E	890	19202	1890	2365	NP	NP
240.	33-2S-4E	918	1989	2078	2600	NP	NP
241.	14-2S-3E	992	19781	2173?	2957	NP	NP
242.	8-2S-3W	981	21633	2643	3242	NP	NP
243.	29-2S-3W	1002	21161	2485	3093	NP	NP
244.	15-2S-3W	1019	21963	2639	3235	NP	NP
245.	18-2S-4W	940	22527	2489	3016	NP	NP
246.	6-2S-5W	963	21638	2516	3054	NP	NP
247.	27-2S-5W	972	22096	2283	2780	NP	NP
248.	14-2S-6W	963	864	2435	2960	NP	NP
249.	31-2S-12W	857	13483	2080	2317	NP	NP
250.	29-2S-16W	665	5971	1397	1926	NP	NP
251.	35-2S-16W	771	5229	1553	1939	NP	NP
252.	32-3S-11E	580	-----	595	----	1080	----
253.	7-3S-10E	632	17574	850	----	----	----
254.	29-3S-10E	617	-----	651	----	1246	----
255.	1-3S-3E	924	18701	2164	2630	NP	NP
256.	8-3S-4E	945	21309	2220	2533?	NP	NP
257.	8-3S-4E	947	18983	2045	2503	NP	NP
258.	8-3S-4E	963	19231	2095	2488	NP	NP
259.	9-3S-9E	656	-----	948	2238	1647	----
260.	15-3S-9E	637	19738	778	----	----	----
261.	32-3S-1W	988	22252	2142	2705	NP	NP
262.	19-3S-2W	994	21966	----	2930	NP	NP
263.	5-3S-3W	1012	22742	2402	2956	NP	NP

No.	Location	Elevation	Permit No.	Salina Top	Niagaran Top	B-Evaporite Top	A-2 Evaporite Top
264.	14-3S-3W	991	22107	2251	2726	NP	NP
265.	36-3S-4W	1036	21585	2225	2686	NP	NP
266.	4-3S-4W	976	21702	2300	2862	NP	NP
267.	15-3S-4W	1029	21432	2240	2720	NP	NP
268.	3-3S-4W	991	21912	2326	2822	NP	NP
269.	23-3S-4W	1048	21416	2330	2914	NP	NP
270.	14-3S-8W	961	20241	1955	2478	NP	NP
271.	5-4S-11E	575	-----	----	----	1060	----
272.	35-4S-10E	585	-----	450	1390	NP	NP
273.	1-4S-9E	621	19260	740?	1709	NP	NP
274.	18-4S-9E	637	9546	700?	1242	NP	NP
275.	26-4S-8E	637	19214	625	1182	NP	NP
276.	26-4S-7E	674	930	----	1675	NP	NP
277.	10-4S-5E	859	19074	1418	1854	NP	NP
278.	32-4S-5E	875	19778	1390?	1995	NP	NP
279.	28-4S-4E	889	1877	----	2400	NP	NP
280.	7-4S-1E	987	21982	2163	2615	NP	NP
281.	18-4S-1W	----	17807	2110	2585	NP	NP
282.	33-3S-1W	1069	22568	2050	2534	NP	NP
283.	8-4S-2W	1034	21534	2113	2620	NP	NP
284.	7-4S-3W	1010	21752	2093	2744	NP	NP
285.	3-4S-3W	1031	20894	2207	2800	NP	NP
286.	28-4S-3W	1032	22265	1946	2456	NP	NP
287.	13-4S-5W	974	21413	1966	2592	NP	NP
288.	21-4S-6W	947	22476	1815	2340	NP	NP
289.	4-4S-7W	919	22620	1863	2260 ?	NP	NP

No.	Location	Elevation	Permit No.	Salina Top	Niagaran Top	B-Evaporite Top	A-2 Evaporite Top
290.	35-4S-19W	669	7026	1029	1409	NP	NP
291.	7-5S-7E	679	17767	842	1434	NP	NP
292.	10-5S-7E	667	19419	804	1625	NP	NP
293.	13-5S-5E	710	19333	938	1560	NP	NP
294.	14-5S-4E	856	20036	1337	2000	NP	NP
295.	16-5S-6E	701	3368	895	1590	NP	NP
296.	1-5S-1W	1066	19198	----	2536	NP	NP
297.	35-58-1W	1120	22749	1936	2365	NP	NP
298.	24-5S-2W	1134	21224	1950	2387	NP	NP
299.	35-5S-3W	1186	20299	1920	----	NP	NP
300.	23-5S-3W	1175	22381	1946	2396	NP	NP
301.	16-5S-3W	1111	21688	1890	2362	NP	NP
302.	2-5S-3W	1058	21216	1910	2333	NP	NP
303.	11-5S-4W	1052	21373	1880	2308	NP	NP
304.	5-5S-5W	966	21862	1814	2381	NP	NP
305.	28-5S-5W	1024	20322	1762	2315	NP	NP
306.	4-5S-6W	975	19538	1802	2370	NP	NP
307.	2-5S-7W	928	20355	1790	2375	NP	NP
308.	20-5S-7W	927	21694	1695	2205	NP	NP
309.	17-5S-9W	875	22242	1589	2120	NP	NP
310.	18-5S-14W	894	1271	1500 ?	1715	NP	NP
311.	12-5S-17W	738	19137	1065	1445	NP	NP
312.	12-6S-9E	592	13867	220	741	NP	NP
313.	7-6S-7E	668	19263	555	1244	NP	NP
314.	1-6S-5E	682	19325	825	1420	NP	NP
315.	22-6S-3E	849	21637	1552	2117	NP	NP

No.	Location	Elevation	Permit No.	Salina Top	Niagaran Top	B-Evaporite Top	A-2 Evaporite Top
316.	18-6S-1W	1196	21109	1903	2349	NP	NP
317.	4-6S-2W	1181	22180	1906	2385	NP	NP
318.	26-6S-2W	1194	21594	1790	2220	NP	NP
319.	32-6S-2W	1180	21771	1763	2187	NP	NP
320.	1-6S-4W	1045	21745	1765	2128	NP	NP
321.	1-6S-5W	1063	19967	1672	2145	NP	NP
322.	29-6S-8W	866	21519	1405	1855	NP	NP
323.	30-6S-8W	906	20700	----	1860	NP	NP
324.	7-6S-10W	876	19599	1415	1903	NP	NP
325.	13-6S-11W	866	2823	1347	1771	NP	NP
326.	27-6S-11W	823	21155	1190	1685	NP	NP
327.	1-6S-16W	760	-----	1130?	1440	NP	NP
328.	4-6S-19W	626	19529	800	870	NP	NP
329.	15-7S-8W	---	20685	1510	1710	NP	NP
330.	4-7S-7E	658	19823	350	1054	NP	NP
331.	34-7S-6E	679	19563	170	810	NP	NP
332.	2-7S-5E	708	983	750?	1385	NP	NP
333.	7-7S-1E	956	9800	1520	1938	NP	NP
334.	29-7S-1E	911	22716	1278	1709	NP	NP
335.	8-7S-1W	1131	21782	1677	2113	NP	NP
336.	24-7S-2W	1064	22537	1550	1976	NP	NP
337.	3-7S-3W	1151	21571	1635	2020	NP	NP
338.	3-7S-4W	1104	21910	1609	2005	NP	NP
339.	10-7S-7W	963	18528	1413	1775	NP	NP
340.	2-7S-13W	928	570	1280	1665	NP	NP
341.	36-7S-14W	904	17414	1028	1231	NP	NP

No.	Location	Elevation	Permit No.	Salina Top	Niagaran Top	B-Evaporite Top	A-2 Evaporite Top
342.	18-8S-4W	1038	21820	1295	1655	NP	NP
343.	15-8S-15W	791	8075	1173	1325	NP	NP
344.	8-8S-20W	647	6364	523	644	NP	NP
345.	4-9S-3W	1020	14088	1322	1764	NP	NP
346.	5-9S-4W	1072	21773	1270	1960	NP	NP
347.	22-4S-2W	1091	21740	2130	2570	NP	NP
348.	2-7S-17W	769	13879	1063	1225	NP	NP
349.	8-8S-7E	668	22737	197	711	NP	NP
350.	28-8S-6E	690	5031	80	675	NP	NP
351.	2-8S-7E	642	19723	60	690	NP	NP
352.	32-8S-4E	714	10448	550	1170	NP	NP
353.	18-9S-4E	717	16693	892	1413	NP	NP
354.	27-8S-1E	813	21916	1066	1566	NP	NP
355.	5-8S-1W	944	22147	1320	1740	NP	NP
356.	11-8S-1W	918	22821	1263	1720	NP	NP
357.	21-8S-1W	904	22819	1186	1638	NP	NP
358.	26-14N-2E	649	-----	6120	8690	7170	7785