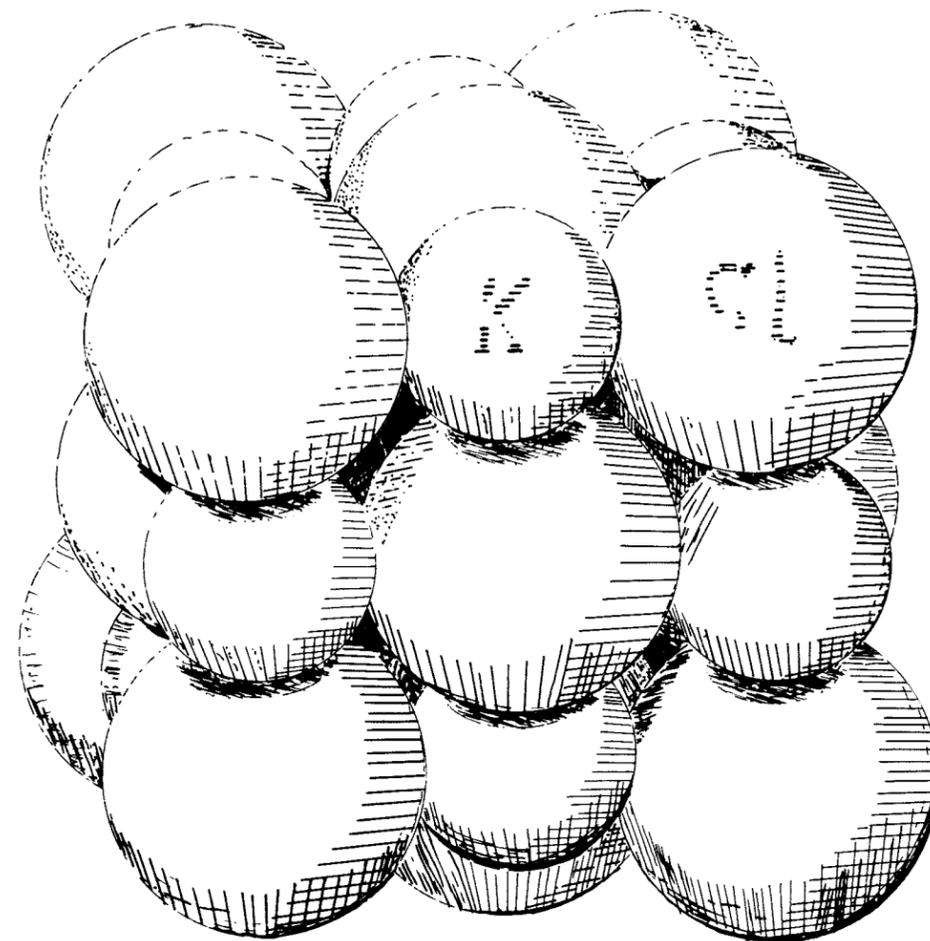


POTASSIUM SALTS-POTASH-
OF THE SALINA
A1 EVAPORITE
IN THE MICHIGAN BASIN



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Geological Survey Division

Report of Investigation 25

POTASSIUM SALTS (POTASH)
OF THE SALINA A-1 EVAPORITE
IN THE MICHIGAN BASIN

by

Ronald C. Elowski

Lansing, Michigan
1980

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Preface

The Oil and Gas Section of the Michigan Geological Survey has a prime responsibility in the administration and enforcement of Act 61, Public Acts of 1939, as amended. This Act, known as the Oil and Gas Act, was passed to provide for regulation of oil and gas drilling activity in Michigan to prevent waste of resources and promote good conservation practices. The filing of reports and well records was mandated in the Act.

Petroleum geologists in the Subsurface and Petroleum Geology Unit of the Oil and Gas Section have the responsibility for maintaining, updating and making available various well records filed with the Supervisor of Wells. These geologists use information from the records to research various topics relating to petroleum geology. In a general way, such published projects are aimed at the prevention of waste by pointing out new areas for exploration or new ways to look at previously developed oil and gas areas. And, further, they are of use to the consultant geologist and to others actively searching for oil and gas resources.

This report will be helpful to those looking for new areas to explore for oil and gas. It will also be a source of data on Michigan's potash deposits. At the same time, it should be useful to anyone studying the evaporites of the Michigan Basin in general, but particularly the A-1 Evaporite of the lower Salina Group.

I wish to thank Garland D. Eells, Michigan Geological Survey, for many helpful suggestions and encouragement during the production of the report. I also wish to thank D. Michael Bricker for suggesting the study. Ron Brown of P.P.G. Industries, Inc., Chemical Division in Regina, Saskatchewan, was helpful in the interpretation of some of the geophysical well logs. Other Geological Survey Division personnel instrumental in bringing this report to final form for publication are Beverly L. Champion, editing; Gregory A. Wilson, drafting and cartography; Donald R. Raymond for cover drawing; Steven E. Wilson, layout and word processing; Margaret Schineman and Bettie Foldi, rough draft typing; and Lois J. DeClaire, final manuscript typing.

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POTASSIUM SALTS (POTASH) OF THE SALINA A-1 EVAPORITE
IN THE MICHIGAN BASIN

Abstract

More and more the study of paleoenvironments is becoming important to geologists in the search for resources. Perhaps chief among these geological resources at the present time is petroleum. And to the petroleum geologist one of the most important paleoenvironments is that of evaporite deposits. Evaporites are important throughout the world as caprock for various carbonate petroleum reservoirs. Salt domes along the Gulf of Mexico form important reservoirs in Texas and Louisiana.

The Michigan Basin is a prime example of a carbonate-evaporite basin, and it has been used as a model by many authors who write about evaporites and evaporite origins. This study has focused on the Michigan Basin, with the Salina Group rocks, particularly the A-1 Evaporite formation, as the subject. Much data for this report was gathered from oil and gas wells drilled within the past decade or two. The gamma ray logs recorded in these wells were the major tools used to define and examine the potash salt beds within the A-1 Evaporite.

This investigation involves the configuration of the potash zone within the vertical section of the A-1 Evaporite and the extent of the potash throughout the Michigan Basin. Structure contour and isopach maps of the potash zone in the basin are presented. In addition, a separate section with discussion on the relationship of the potash salts to the pinnacle reefs in the northern Michigan Niagaran reef trend has been included. This section contains a series of five maps which, together, show the extent and structure of the potash as it relates to the pinnacle reefs. A cross section from an off-reef well with an indication of a small amount of potash to an edge-reef well without potash is also included.

The author believes that this paper presents a usable tool for the exploration for new and as yet undrilled Niagaran pinnacle reefs in Michigan. Also, those who are interested in a source of potash may find this publication useful.

Introduction

One of the most widely explored rock sequences in Michigan is the Niagaran Series of Middle Silurian age. Drilling wells to the Niagaran rocks affords the opportunity to look not only at the Niagaran rocks, but also to investigate certain salt beds found in the Upper Silurian Cayugan Series immediately above. The purpose of this report is to investigate the A-1 Evaporite in general, but specifically the potash salts found within the salt phase of the A-1 Evaporite Unit in the Michigan Basin.

The A-1 Evaporite is the lowest unit of the Salina Group except near the outer edges of the basin and on top of the Niagaran pinnacle reefs where the A-1 Carbonate rests directly on the Niagara formation. In the Michigan Basin, the A-1 salt together with the A-1 anhydrite make up the A-1 Evaporite Unit, although both the salt and the anhydrite do not exist everywhere together over the whole range of the A-1 Evaporite. The A-1 Evaporite may reach a maximum thickness of 500 feet (Matthews, 1970, p. 21) in the deepest part of the basin, but the thickest section observed in gamma ray logs used in this study is 448 feet. Generally the thickest sections of A-1 Evaporite are almost entirely salt, possibly with minor amounts of anhydrite at the base. In the thinnest sections where the A-1 Evaporite is still recognizable, it is almost entirely anhydrite with minor amounts of evaporitic dolomite.

When the potash salts are present, they occur in the upper half of the salt section of the A-1 Evaporite, as reported by Matthews (1970) and Schmalz (1969). They occur as multiple beds in central basin wells or as a single massive bed in wells near the edge of potash occurrence. In this report, gamma ray log sections and maps show the thicknesses of the potash beds and structure contours on the top of the potash zone. A relationship between the northern Michigan Niagaran reefs and the potash occurrence is illustrated and explained.

Purpose

Over the years the Michigan Geological Survey has received a number of inquiries about potash occurrences in the State, some from industry and some from colleges and universities. These inquiries have led to this investigation, which is feasible since abundant well control is now available.

The purpose of this report is to provide useful and easily obtainable information about the potash salts of the Michigan Basin. This paper will be useful not only to brine producing companies, but also to those exploring for petroleum.

Stratigraphy

A review of the general stratigraphy involved in this investigation is pertinent to an

understanding of the origin of the potash of the Salina A-1 Evaporite. Of primary interest are the lower formations of the Salina Group of Late Silurian age. But the subsurface relationship of these formations with the upper Niagaran Series of Middle Silurian age is also discussed. The A-1 Evaporite formation of the lower Salina Group and the halite and potash salts contained therein are the principal topics of this paper. Coincidental to this study is the relationship between the A-1 Evaporite and the pinnacle reefs of the upper Niagaran Series.

The term Niagara Group dates back at least as far as 1842 when J. Hall made reference to it in the American Journal of Science (Wilmarth, 1938). The term probably evolved long before that, based on studies of the geology of exposures in Niagara County, New York and especially along the gorge of the Niagara River (Wilmarth, 1938). At the present time, in reference to Michigan outcrops, the term Niagara or Niagaran is used as a series name for several groups and their associated formations. As stated by Johnson et al. (1979), the group names are Burnt Bluff (oldest), Manistique, and Engadine (youngest). Prior to the Johnson publication the Engadine had been given only formational status. Ehlers and Kesling (1962) said: ...the Engadine has been retained as a formation. When additional beds are available for study, it will perhaps rank as a group with several formations.

As predicted by Ehlers and Kesling, the Engadine has been raised to group status and divided into several formations.

In the subsurface the formal outcrop terminology is not used. Instead, a series of informal and poorly defined terms has evolved based on drillers' descriptions and, to a minor extent, geophysical log responses. Such informal terms as 'brown Niagaran', 'gray Niagaran', and 'white Niagaran' are based mainly on color, while the informal term 'Clinton' may or may not be related to the Clinton shale of New York State.

The Niagara or Niagaran has long been known from outcrop studies to contain reefs of various origin and shape, but only in the last couple of decades has the full extent of the Niagaran pinnacle reef network in Michigan been realized. Oil and gas drilling activities of some of the major oil companies operating in Michigan have centered around finding the isolated reefs or groups of reefs which appear to be surrounded by evaporites of the younger Salina Group, thus forming excellent traps for petroleum. Most petroleum geologists in the State assign these pinnacle reefs to the brown Niagaran. Acceptable or not, the brown Niagaran is a convenient term. Likewise, the gray Niagaran has generally been used by petroleum geologists as the base of the pinnacle reef facies or brown Niagaran.

The Salina Group of the Michigan Basin is a sequence of evaporites, carbonates, argillaceous carbonates and shales of Late Silurian age which makes up the lower part of the Cayugan Series. The upper part of the Cayugan consists of the Bass

Islands Group. The surface type section for the Salina Group is in New York State and consists of four formations, the Vernon, Syracuse, Camillus, and Bertie (Rickard, 1966). In Michigan outcrops, only two formations are recognized as the Salina Group, the older Pte. aux Chenes Shale, and the St. Ignace Dolomite. Both outcrop names are from the Mackinac Straits region of the Northern Peninsula of Michigan (Michigan Geological Survey Division, Chart 1, Stratigraphic Succession in Michigan, 1964).

The Salina Group is more easily understood by observing the subsurface section, as Landes (1945) did in Michigan. Landes is responsible for much of the present nomenclature of the subsurface Salina Group in the Michigan Basin and surrounding areas. Starting at the base of the group, Landes proposed formational divisions using the letter notations A through H. The H designation was to replace the term Bass Islands but was never widely accepted. Evans (1950) later divided the A formation into an A-1 and an A-2.

It has since become popular, in the Michigan Basin, to designate an A-1 Evaporite and A-1 Carbonate, and an A-2 Evaporite and A-2 Carbonate. In a stratigraphic cross section, Ellis (1962) proposed six divisions for the F Evaporite formation of Landes, based on an observed repetitious sequence of halite, shale and/or carbonate beds. The divisions were, from the bottom upward, F Salt 1 to F Salt 6; but only in basin center wells were all six units clearly discernible. The salts of the upper F Unit tend not to be present in the basin margin areas, especially in the south and west. This paper will be concerned mainly with the A-1 Evaporite and that area of the Michigan Basin where the A-1 Evaporite is mostly halite with some potash beds.

Two major schools of thought prevail regarding the origin of evaporites. One concept is that evaporites are formed in a deep water environment; another theorizes shallow water conditions producing sabkha evaporites. In the literature of the Michigan Basin Salina evaporites, most investigators favor the deep-water evaporite theory (Goldsmith, 1969; Schmalz, 1969; Matthews, 1970; Matthews and Egleson, 1974). The author attempts to explain the Salina Group evaporites in general and the potash of the A-1 Evaporite in particular in terms of the deep water theory.

Method of Investigation

Since the potash salts have very few characteristics other than radioactivity to distinguish them from other salts, the gamma ray log was the primary tool used in this investigation. The better known potash salt minerals, kainite, carnallite, and sylvite, contain the element

Mineral	Composition
kainite	MgSO ₄ KCl · 3H ₂ O
carnallite	KCl MgCl ₂ · 6H ₂ O
sylvite	KCl

potassium. Potassium has a radioactive isotope K^{40} with a half life of 10^9 years which undergoes radioactive decay, releasing gamma rays to form argon (E. H. Sargent & Co., 1964). The release of gamma rays from K^{40} causes the radioactive response for potash salts on the gamma ray log. Another useful log is the caliper log. Although the fluid used in drilling is usually saturated with NaCl by the time the A-1 salt is reached, it is very rarely saturated with any of the potash salts and thus will dissolve away some of the potash. The caliper log is designed to show washout of salts or caving of the hole by taking a mechanical reading of the sides of the well bore.

Aside from the gamma ray and caliper logs, apparently the density and sonic logs are also sensitive to high concentrations of potash. Density logs tend to show lower readings for potash than for halite, and sonic logs tend to show increased transit times or completely erratic behavior, possibly due to washout of the potash salts during drilling.

On most gamma ray logs a relatively pure halite bed reads very low on the scale of the log (between 15 and 30 API units), depending on how the recorder was originally calibrated. If potash is present, the readings on the gamma ray scale are very different, ranging from 45 API units to off-scale at over 150 API units. The gamma ray reading was used in conjunction with readings on the sonic, density or neutron log to determine thickness and depth of the potash in a given well. The sonic, density and neutron log curves do not change radically from a zone of halite to a zone of potash occurrence, but when these curves are used along with gamma ray log curves, the changes are noticeable and aid in confirming the presence of the potash.

In the course of this investigation over 1,000 well logs were inspected. Most of them were from the northern counties in the Southern Peninsula where the majority of wells penetrate Niagaran rocks. Gamma ray logs were recorded in most of the wells drilled to Niagaran rocks or deeper formations within the area where the A-1 Evaporite is a salt.

Information from the logs was recorded on data sheets, and included the location, elevation from which logs were measured, and depth to top and bottom of the potash bed. In the case of a directional hole, the true vertical depths were calculated for the subsea elevations. After the true subsea elevations were found for top and bottom of potash beds the thickness of the bed was determined. Thicknesses were plotted on a small scale (6 miles to the inch) map of the Southern Peninsula to determine the lateral extent of the potash in the A-1 salt. The same data were plotted on larger scale (1 mile to the inch) maps of some of the northern counties to determine the relationship between the potash salts occurrence and the Niagaran Series pinnacle reefs. These work maps of Manistee, Grand Traverse, Kalkaska, Otsego, Mason and Montmorency counties are not

included in this report. Subsea elevations on the top of the potash occurrence were then plotted on the Southern Peninsula map to see how, or if, post-Salina Formation subsidence and deformation had affected the beds since deposition. It is assumed that the top of the potash salt occurrence is everywhere time equivalent, or nearly so.

Previous Work

Dr. A. W. Grabau was quoted by R. A. Smith (1914, p. 325) as having written the following in a letter to R. C. Allen (date unknown):

The present is a good time for the discovery of potash salts in Michigan. As I read the Silurian history, the lowest salt beds under Detroit ought to carry the potash salts similar to those found at Stassfurt the history being the same. This is true only for the lowest bed. If that does not contain it, then there is no potash in the deposits in the East (i.e. east of the Rocky Mountains). I believe it is really worth making a test of this bed.

Dr. A. W. Grabau was correct in his prediction that the lowest salt should contain potash; but he was incorrect in naming the Detroit area, where the lowest salt is, in most cases, the Salina Group B salt. Grabau's comparison of Michigan deposits to those in Germany was also valid, except that he lacked the central and northern Michigan Basin well data that is available today. However, Grabau's letter to Allen was the first reference to potash in the Michigan Basin.

The term Salina Group was first used by Dana in 1863 in New York. Dana's Salina Group, according to Allings and Briggs (1961) was ". . . for the time corresponding with the Onondaga salt group and the Guelph (Galt) limestone." Landes in 1945 divided the Salina and Bass Islands groups of Michigan into the presently-used letter notations.

A very detailed comparison of the A-1 Evaporite in a core from a well in Newaygo County and some F Unit salts in the International Salt Company mine in Detroit was done by Dellwig (1955). Microscopic analyses of crystal structures, inclusions, and accessory minerals were performed. He found polyhalite and carnallite present but only as minor constituents in the salt beds, not as bedded potash salts. However, Dellwig, by studying inclusions and bubbles in the salt crystals, presented some good evidence to support his theories about the temperature of the brine (32°-48°C) from which "hopper" salt crystals were deposited as well as other aspects of salt deposition.

Most early investigators realized that the large volumes of salt within the Salina Group could not have precipitated from one basin full of seawater. Perhaps the most believable mechanism for bringing such volumes of salt into the basin is a continuous influx of seawater. Melhorn (1958)

proposed a "delicate balance . . . between sinking, evaporation, and influx of marine waters", and stated that "at no time did evaporation processes approach completion." Melhorn thus would seem to preclude the deposition of potash salts in the Michigan Basin.

Ells (1967, p. 10), in describing the A-1 Evaporite, states:

It is a clean salt over most of the basin interior, but a few thin shale or carbonate lenses occur near the middle of the unit in the deeper parts (Correlation Section I).

"Correlation Section I" is a tracing of the gamma ray log curve for the Brazos Oil & Gas Company, et al, State-Foster #1 in Ogemaw County. The thin shale or carbonate lenses mentioned by Ells are actually potash salts. In any event Ells recognized these lenses as occurring near the middle of the unit in the deeper parts of the basin interior. This occurrence was later predicted by Schmalz (1969) and observed by Matthews (1970) and Matthews and Egleson (1974) as the location within thick salt sections in general, and the A-1 salt in particular, for the occurrence of potash salts.

Anderson and Egleson published an article, "Discovery of Potash in the A-1 Salina Salt in Michigan" in Sixth Forum on Geology of Industrial Minerals (1970). A more detailed report by Matthews dealing with the extent and potential of the deposit is in the same publication. Both reports are related to the Dow Chemical Company research and stem from tests for bromine in a well core at Midland, Michigan. While Anderson and Egleson were more concerned with the actual identification and confirmation of the existence of potash, Matthews correlated the occurrence to several deep wells in the State. Matthews' paper is more comprehensive and contains maps and cross sections showing the extent of the potash in the State as well as theories concerning the formation of the salts. These two papers were the first publications dealing expressly with potash salts in the A-1 Evaporite in the Michigan Basin.

Anderson and Majeske (1970) collaborated in yet another paper in the same publication. This third paper dealt with the detection of potash by analysis of drilling fluid as a means of correlation and further confirmation of the extent of the potash in the A-1 salt. A paper by Matthews and Egleson (1974) in the Fourth International Symposium on Salt - Northern Ohio Geological Society was a combination of Matthews' (1970) work and Anderson and Egleson's (1970) paper with added gamma ray log correlation data. This paper appears to be the last publication dealing principally with the A-1 potash in the Michigan Basin. At least one later publication, Nurmi and Friedman (1977), mentions the A-1 potash in relation to Niagaran reefs.

Appearance of Potash on Gamma Ray Logs

Throughout most of the Michigan Basin the A-1 potash salt probably occurs as a multiple bed zone, as observed in Midland County (Figure 1) and Newaygo County. But along the basinward edge of the northern Niagaran reef trend the zone is more compact and lacks the distinct beds of the Midland County zone. The Midland County beds are separated (at least on gamma ray logs) by less radioactive beds, probably halite. It is probably safe to assume that the multiple bed zones in Midland County are correlatable with the more massive zones along the basinward edge of the northern Niagaran reef trend.

Aside from the vertical spacing of the beds making up the A-1 potash zone, there are two other distinctions between the Midland County potash zone and the potash zone along the basinward edge of the northern Michigan Niagaran reef trend. Probably the most noticeable difference is the stratigraphic location of the zone within the A-1 salt. In the Pure Oil Company, Merton Emery #1 well in Midland County, the potash zone is in the center of the A-1 salt section. In wells elsewhere in the basin (Crawford County in particular), the potash, where present, occurs in the upper half to one-third of the A-1 salt section. Some wells in Crawford and Oscoda counties appear to have an A-1 potash zone immediately below the A-1 Carbonate. They also have a salt section between the potash zone and the underlying Niagaran which is almost the exact thickness of the salt section between the potash zone and the Niagaran in the Merton Emery #1 well (Figure 1) in Midland County. This similarity in salt thickness between the potash zone and the underlying Niagaran seems to indicate a similar depositional history for the A-1 salt in these two areas, at least to the time of the potash deposition.

Another difference between the Midland County well and various wells along the basinward edge of the northern Michigan Niagaran reef trend is the apparent radioactivity of the potash according to the gamma ray logs. The API Unit, devised by the American Petroleum Institute, is the standard to which present day gamma ray logs are calibrated. In the Merton Emery #1 well in Midland County (Figure 1), the maximum gamma ray response for any of the beds in the potash zone was 105 API units. Some of the more radioactive potash beds in wells in Crawford, Kalkaska, and Manistee counties go off scale at over 200 API units. Since the intensity of readings from the gamma ray logging tool in a given well depends on the distance from the tool to the source of radiation, as well as the actual concentration and purity of the radioactive source, a high degree of washout in a potash zone could cause deceptively low readings on a gamma ray log. This washout problem could account for the lower gamma ray readings of the potash beds in the Merton Emery #1 well, compared to several wells along the northern Michigan Niagaran reef trend. But if one assumes that the extent of washout was the same

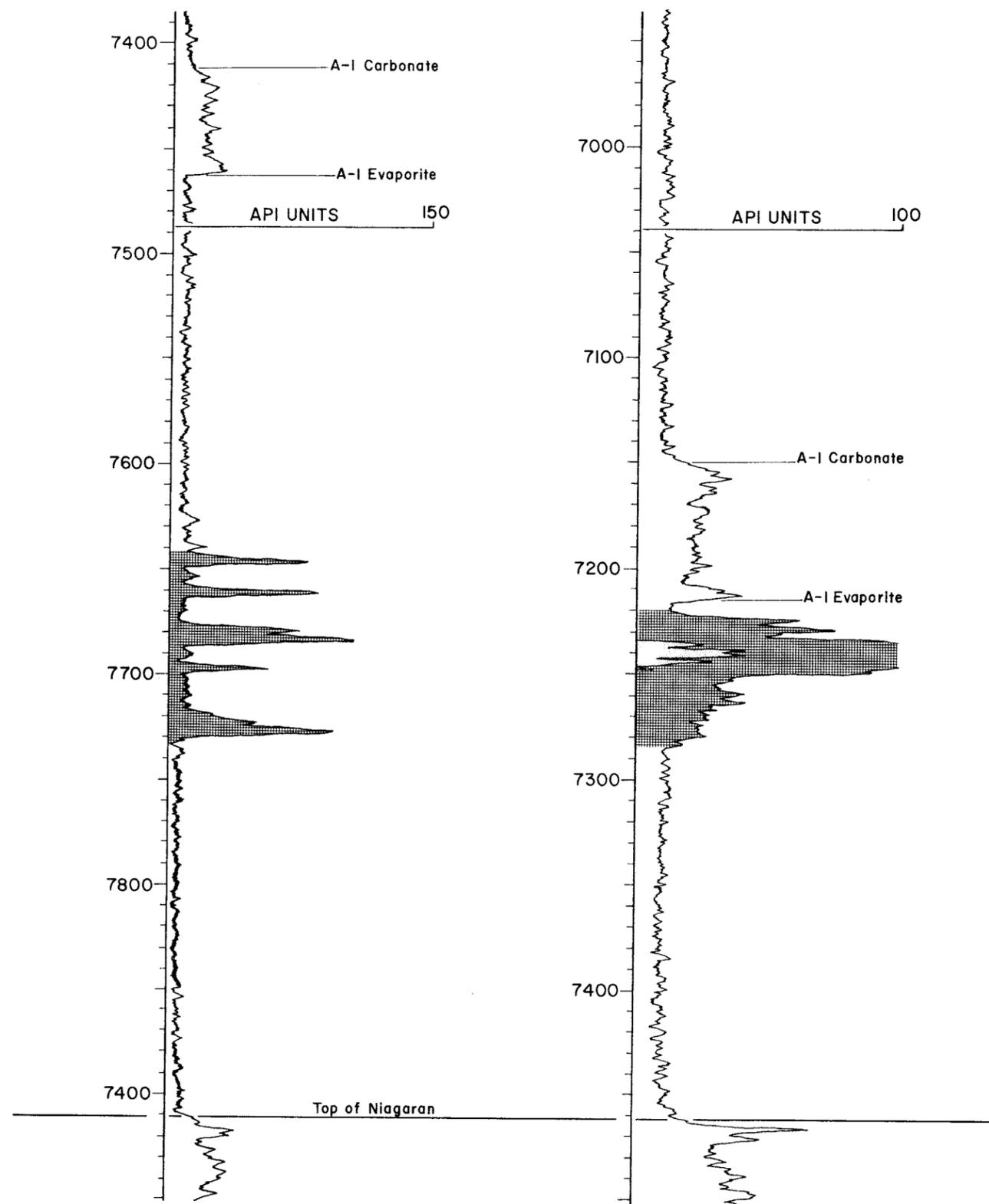


Figure 1. A comparison of two gamma ray logs showing the configuration of the potash salts in the A-1 Evaporite. Log on the left is from the Pure Oil Company, Merton Emery #1, permit number 23849, Section 21, Porter Township, Midland County, rotary bushing elevation 694.7 feet. Log on the right is from the Northern Michigan Exploration Company et al., State-Lovells #1-26, permit number 29036, Section 26, Lovells Township, Crawford County, kelly bushing elevation 1,293 feet.

in both locations, the potash in the wells along the northern Michigan Niagaran reef trend must be more concentrated than in Midland County.

Extent of Potash Salts

Although potash salts in the A-1 Evaporite can be found in the proximity of the northern Niagaran reefs, these potash salts do not extend as far south or east as Eaton, Ingham, or St. Clair counties where Niagaran reefs are also found. However, the author found what appears to be a trace of potash salt in the A-2 Evaporite in a well in Oakland Township, Oakland County. The maps (Figures 2 and 3) show an area of potash in the A-1 Evaporite similar to that depicted by Matthews (1970, p. 22), and Matthews and Egleson (1974, p. 19, 23, 24, 25). This area would tend to indicate more dilute brines entering the basin from the east and south and possibly as far to the northeast as Georgian Bay. There is also indication of a basin outlet in the Allegan and Barry counties area in which some minor amounts of potash salt were deposited. It would appear that the eastern and southeastern parts of the Michigan Basin, in Salina A-1 Evaporite time, contained more dilute brines than the central, northern, and western portions of the basin. However, due to a lack of A-1 Evaporite wells in Arenac, Bay, Iosco and Saginaw counties, conclusions as to the total eastern extent of the potash salts in the A-1 Evaporite may be a bit premature.

The structure contour map (Figure 2) drawn on the top of the potash salt interval in the A-1 Evaporite shows highest subsea elevations in the Allegan-Barry County area and in Montmorency County. The higher elevations in Allegan and Barry counties on the top of the potash zone correspond to a lobate extension of the main potash basin. Whether the high elevations on the top of the zone in Montmorency County indicate a similar extension in the Montmorency-Presque Isle County area is not known, but an absence of subsidence in that area, at least, is indicated.

Conclusions

As a result of observations and reading numerous articles relating to evaporite deposits, several conclusions have been reached concerning the origin of the potash salts in the A-1 Evaporite and the origin of the lower part of the Salina formation (A-1 Evaporite through the B Unit). I agree with several researchers in the field of evaporites (Schmalz, 1969; Dellwig, 1955; Borchert and Muir, 1964; Matthews, 1970; Matthews and Egleson, 1974) regarding depth of brine in the basin at the time of deposition, and methods of concentrating the brines.

With the discovery of present day anhydrite deposits forming in coastal sabkhas along the Persian Gulf, sabkha-type evaporite origin has been applied to all types of anhydrite and halite deposits. It can not be applied to the thick salt

sections in the lower Salina formation because rates of subsidence necessary to contain the newly forming evaporites would be extreme.

Concerning the supposition that the evaporite basin subsided at or near the rate of evaporite accumulation, I think Robert F. Schmalz (1969, page 800) stated it best:

... Evaporite deposits more than 300m thick are widespread, and drilling in some areas has shown the presence of evaporite sequences more than 3000m thick. Estimates of the rate of salt accumulation in each of these areas agree substantially with rates observed in modern salinas. If the shallow-salina model is applicable to such thick deposits, the rate of subsidence of the depositional basin in each case must have equaled the rate of salt accumulation. Such subsidence rates are both spectacular and geologically unreasonable.

What Schmalz advocates is a basin already formed at the time of the initial evaporite deposition, with a depth equal to or slightly less than the ultimate thickness of the evaporite deposit, assuming that some subsidence will occur at a more realistic rate during evaporite deposition.

In the Michigan Basin during middle to late Silurian time, the Niagaran age reefs (both massive main bank reefs and pinnacle reefs) grew outward into the deeper basin, from the shallower arches and shield areas surrounding the basin at that time. They grew thus in response to the lack of space below wave base and because of occasional low sea level exposures of the higher reefs. The environment for the maintenance of reef species is limited by water temperatures and perhaps water salinity at the lower limit, and erosion by waves and tide exposures at the upper limit; and available nutrients are always a factor. If the space between these two limits is filled with previously grown reefs and their accompanying debris, the younger reef-forming organisms must pioneer new territory basinward of the crowded and filled neighborhood around the basin rim. Eventually, the basin rim becomes so crowded with reefs and reefal debris that a slight drop in sea level severely restricts the flow of fresh sea water into the basin except through channels that may have been left open in the surrounding reef banks. Such channels obviously indicate locations not favorable to reef settlements. Possibly the inflowing sea water was too cold, or water from neighboring basins was too saline to contain any nutrients for support of reefal life forms.

Because of the apparent extent of the A-1 potash zone in the Michigan Basin (Figures 2 and 3), I believe there must have been two main inlets and possibly two minor inlets into the basin. The first major inlet, at least from the beginning of A-1 Evaporite time to post-A-1 potash time, was from the New York Basin across the Chatham Sag

(Dellwig, 1955). Briggs and Pollack (1967), in their digital model of the Michigan Basin during Salina time, show the passage over the Chatham Sag as an outlet. This might be true for later Salina deposition, but during the time of A-1 Evaporite deposition, the Chatham Sag would have to be an inlet, as Rickard (1966, page 35) describes:

Salt beds several hundreds of feet thick occur in divisions A and B in Michigan.

In the Appalachian basin, much thinner salt beds occur in Unit B but none are known from Unit A.

This would indicate less concentrated brines in the Appalachian Basin in early Salina time than in the Michigan Basin. While brines were concentrated enough for halite deposition in the Michigan Basin in A-1 time, the brines in the Appalachian Basin were not so concentrated. In my opinion, the Appalachian (or New York) Basin in A-1 Evaporite time must have had an inlet from the major oceans of the time and an outlet into the Michigan Basin, thus allowing somewhat more concentrated brines into the Michigan Basin than would otherwise be available from the outer oceans (a view supported by Anderson and Egleson, 1970, p. 18).

Further evidence for a major inlet across the Chatham Sag, in A-1 Evaporite time at least, is the thin anhydritic A-1 Evaporite found in many off-reef wells in Oakland, Macomb, and St. Clair counties. These same wells show a massive A-2 salt section. The author concludes from these facts that the Chatham Sag operated as a Michigan Basin inlet in A-1 Evaporite time, prohibiting the formation of a thick A-1 salt section in southeastern Michigan, but was either a very minor inlet or an outlet in A-2 Evaporite time and perhaps was an outlet for the rest of Salina time, as Briggs and Pollack (1967) propose.

Another major inlet for the Michigan Basin in A-1 Evaporite time was through what is now Georgian Bay, as proposed by Briggs (1958) and Briggs and Pollack (1967). After looking at the pattern of the A-1 potash (Figures 2 and 3) as well as the stratigraphic location of the potash in wells in Crawford, Oscoda, and Ogemaw counties, the author concludes that the Georgian Bay inlet provided the means for a minor diluting influence in the A-1 Evaporite basin until late in A-1 Evaporite time, when the inlet became a major channel for greater dilution. As Matthews and Egleson (1974) point out, "The recessive salt deposited over the potash, and preserved in mid-basin, is not now present over the northern potash." This is presumably due to the introduction of some new source of dilution in late A-1 Evaporite time which resulted in the redissolving of the halite overlying the potash. I believe that new diluting and/or dissolving source was the Georgian Bay inlet. Perhaps rising sea levels outside the basin finally reached a point in late A-1 Evaporite time that allowed a less restricted flow through the present day Georgian Bay area.

A minor inlet to the Michigan Basin in A-1 Evaporite time might have existed in the southern part of the State. Such a passage was suggested and termed by Briggs (1958) the Clinton inlet. It

was so named because it supposedly passed through the area where the town of Clinton now stands in Lenawee County. The orientation of the A-1 potash zone in the Michigan Basin does not offer direct evidence for the existence of this inlet. Briggs, on the basis of limestone/carbonate ratios, assumes that the inlet was most active during middle Salina time. The fact that the potash zone does not reach as far south as the Niagaran reefs in Eaton or Ingham counties could be indirect evidence for the existence of a source of diluting brine in the area.

Briggs (1958) advocates yet another inlet in the Mason County area called the Ludington River. He bases the existence of this inlet on the low salt content of the Salina Group, a low limestone/carbonate ratio, and lesser thickness of the Salina Group as a whole in the area. If I were choosing a western source for fresher brines on the basis of the A-1 potash zone configuration, it would be farther south, perhaps in the Muskegon County area. The A-1 Evaporite in that vicinity appears to contain no potash; but A-1 Evaporite well control in the Muskegon area is scarce, so any such assumptions should be viewed in that light.

In addition to the inlets mentioned so far in this paper, some evidence has been found for an outlet, or at least an embayment, in A-1 Evaporite time in the Allegan-Barry County area in southwest central Michigan. A study of gamma ray logs reveals that minor but noticeable amounts of potash appear to exist in several wells in Allegan and Barry counties. These occurrences were interpreted by Matthews (1970, page 22) and Matthews and Egleson (1974, page 19) as a lobate extension of the main body of A-1 potash. I concur with this interpretation (Figures 2 and 3). If such an interpretation is correct, a low area is indicated, where dense potash-forming brines could collect and precipitate potash salts in A-1 Evaporite time. Whether this lobe of the A-1 Evaporite basin actually extended into the Illinois Basin in A-1 Evaporite time is not known, but it may have been an active outlet or inlet in Niagaran time. Lower water levels in the A-1 Evaporite basin may not have reached over any possible sill or reefal debris which would have only partially blocked that passage in Niagaran time when water levels are assumed to have been higher.

General Observations Along Northern Michigan Niagaran Reef Trend

Since most of the data for this report is from wells along the northern Michigan Niagaran reef trend (Figures 4 through 8), the area deserves special discussion. The deposition of the potash was definitely influenced by the presence of the Niagaran pinnacle reefs.

As stated earlier, some of the highest gamma ray log responses in the A-1 salt occur along this reef trend in off-reef dry holes with thick A-1 salt sections. Mapping the extent of these log responses reveals some interesting relationships between the potash occurrence and the Niagaran reefs.

The maps (Figures 4 through 8) are based on gamma ray responses in the A-1 Evaporite in off-reef dry holes as well as in wells with Niagaran reef sections and little or no A-1 salt.

Along the northern reef trend the thicker sections and perhaps higher gamma ray responses, indicative of potash, occur in the center of embayments between Niagaran reefs. These embayments, as mapped, do not extend more than halfway through the reef trend in most instances, but tend to surround or nearly surround reefs and groups of reefs along the basinward edge of the trend.

Some very subtle changes in the lower Salina formations were observed in a cross section from an off-reef well with minor amounts of potash salts in the A-1 Evaporite to a well with a slight reef build-up. The cross section (Figure 9) extends from the Shell Oil Company, Pulaski-State-Mayfield 5-30, in Section 30, Mayfield Township, Grand Traverse County, through the Shell Oil Company, Pulaski et al 3-30 also in Section 30, Mayfield Township, to the Shell Oil Company, Pulaski 3-19 in Section 19 of Mayfield Township. The Pulaski 3-19 is an oil well with a reef section less than 100 feet thick and a thin A-1 Evaporite section. In an area of Niagaran reefs where potash salts are known to exist in the A-1 Evaporite section off-reef, the disappearance of the potash from the A-1 Evaporite may be the first indication that a reef is nearby. This can readily be seen by comparing gamma ray log curves of off-reef and near-reef wells. Also, the closer the near-reef well is to the reef, the more anhydrite there is in the A-1 Evaporite section. In some of these wells the potash seems to disappear, for the most part, prior to the anhydrite thickening.

Another change noted in cross sections and measurements made from off-reef wells and near-reef wells in the same area is the slight thickening (15 to 20 feet) of the A-1 and A-2 Carbonate sections in the near-reef wells. If a reef build-up in the Niagaran is noted on the electric logs, the thickening of the A-2 and particularly the A-1 Carbonates may no longer be apparent. It is possible that the thickening of the A-2 and A-1 Carbonates is due to the beds being slanted slightly away from the reef. Thus, the vertical wellbore cuts through beds at an angle relative to the plane of the beds, making the section appear thicker. In general, as long as there is some A-1 Evaporite present in a well near a reef, that well will have thicker A-1 and A-2 Carbonate sections than any wells in the area that are farther off-reef.

The thicknesses of the A-2 and particularly the A-1 Evaporites behave the opposite of the A-2 and A-1 carbonates in the near-reef area. These evaporites tend to thin towards the reef and the lithology changes. These thinnings and lithology changes may indicate a slight dilution of brines around the reef at least during the time the A-1 Evaporite and A-1 Carbonate were being deposited. The Niagaran age reef could have been

exposed above the A-1 Evaporite sea. This could have disrupted normal currents in the near-reef area and thus have caused some dilution around the reef by brine mixing; or dilute brines from lower formations could have funneled upward and outward around the reef. The funnelling of meteoric water down through the exposed reef and out the flanks is also a possibility.

In summary, the following changes may be observed in the A units from off-reef wells to near-reef and on-reef wells, starting with farthest off-reef changes:

1. If the potash salt of the A-1 Evaporite is in an area where reefs are known to occur, the potash salts disappear when going toward the reef.

2. At about the same point where the potash salts disappear from the A-1 Evaporite, the anhydrite in the base of the A-1 Evaporite thickens.

3. Where changes 1 and 2 take place, a slight thickening of the A-1 and A-2 carbonates also occurs and continues to the point where the A-1 Evaporite is completely absent; and even then the A-2 Carbonate may continue to thicken onto the reef a bit further.

4. Also, in the zone of changes 1 and 2, a thinning of the A-1 and A-2 Evaporites occurs approaching the reef and continues to a point where the A-1 Evaporite disappears completely and the A-2 Evaporite becomes a relatively thin anhydrite over the reef.

It appears, therefore, that the reef has had an affect on the depositional environment of the lower Salina Group, either by disrupting normal currents and causing dilution by brine mixing, or by funnelling dilute brines through the reef flanks from either lower formations or meteoric water from above.

I should state at this point that these observations apply only to that part of the northern reef trend which lies basinward of the lengthwise center line of the trend. This center line appears to, more or less, mark the northernmost occurrence of the potash salts in the A-1 Evaporite. There are at least two, and possibly three, other changes marked by this trend center line:

1. In general most Niagaran oil wells in the northern reef trend are found north of a line, lengthwise, through the center of the reef trend (Mantek, 1973, page 40).

2. Most sour Niagaran gas and oil occurs south or basinward of the center of the reef trend (Wilson, *).

* Wilson, G. A., 1976, Producing Well Locations Containing Hydrogen Sulfide in the Northern Michigan Niagaran Reef Fields, Michigan Geological Survey, unpublished map.

3. More limestone reefs are found basinward of the northern reef trend center line.

I also observed that the subsea elevations on the top of the potash zone in the A-1 Evaporite along the northern reef trend are lowest in Kalkaska County in the area of Excelsior and Kalkaska Townships. However, if this area were lower during the time of the potash deposition, the potash found in the inter-reef embayments would extend much further into the reef trend than it does because the potash source brines could flow farther into the embayments. Therefore, I assume that the deeper subsea elevations on the top of the potash zone in the area of Kalkaska and Excelsior Townships are due to relative subsidence in the area after the potash was deposited. This is not surprising, however, considering the length of time from late Silurian until now. Many tectonic events could have taken place in that time span. But the major relative sinking along the northern reef trend in all that time appears to have taken place in the Kalkaska and Excelsior Townships area.

Northern Niagaran Reef Trend Conclusions

The writer believes that careful mapping of the A-1 potash along the area of the northern Michigan Niagaran reef trend could reveal a few as yet undrilled reefs. As stated before, the A-1 potash as well as the A-1 salt do not appear to come into direct contact with the Niagaran pinnacle reefs. Some diluting or dissolving influence around the reefs precluded their deposition. The potash salts being much more soluble were, of course, more affected by this diluting influence and disappeared from the A-1 Evaporite section at a greater distance from the reefs than did the A-1 salt. As it disappeared, the A-1 salt tended to grade into an anhydrite toward the reef flank. The anhydrite, and possibly some evaporitic carbonates, are the only lithology(s) of the A-1 Evaporite that are in direct contact with the Niagaran reefs, unless salt plugging is assumed to be part of the A-1 Evaporite. What this means is that the A-1 potash can, in some instances, be used as a near-reef indicator. Unfortunately, this theory appears to be applicable only along the basinward half of the northern Niagaran reef trend, and then is not usable along the entire length of the trend.

In the area along the basinward half of the northern Niagaran reef trend, dry holes can reveal more than just an absence of oil. This is especially true if there is no potash or very little potash present in the A-1 Evaporite. In such instances there is the possibility that a reef is nearby, maybe within a quarter mile or less. The "rabbit ears" of the A-1 Carbonate are probably a better near-reef indicator than the lack of potash. But the lack of potash can at least indicate an area in which to run seismic, and if there are other off-reef dry holes in the immediate area without potash, it may be possible to pick a drillable sight on that basis alone.

Aside from the use of the A-1 potash as a near-reef indicator, its presence between and around the reefs tends to confirm observations by Mantek (1976) and Gill that certain groups of reefs within the main trend line up "oriented at about 15° to the trend's strike" (Gill, 1979, p. 611). Mantek ascribed these linear features to normal faulting related to tension fractures, the reefs presumably growing on the up-thrown edge. Gill's paper contains a map (1979, p. 614) on which are illustrated various zones through the northern Michigan Niagaran reef trend, the zones being types of fluid (gas, oil, water) found in the reefs. The normal sequence of zones from basinward edge outward toward the rim is gas-filled reefs, oil-containing reefs, and water-filled reefs. Exceptions to this sequence are not uncommon, but according to Gill are explainable. The potash-containing embayments within the reef trend generally do not extend farther than the gas-containing reefs, with several exceptions. The farthest reaching embayments of potash tend to correspond to those exceptions noted in Gill's paper. Gill also cites a map by Wilson et al. (1976), stating that wells within the northern Michigan Niagaran reef trend tend to have more "sour" production (higher in H₂S) toward the basinward edge of the trend. These sour wells appear, more often than not, to be surrounded or nearly surrounded by embayments containing potash salt. Also, most salt plugged reefs are within the limits of the potash.

That these observations could be coincidental seems difficult to believe; but they could all be factors explained by or dependent on the slope of that part of the basin. Since the limit of potash occurrence is due to the intersection of the body of dense potash-producing brine with the upward slope of the basin floor, the preformed Niagaran reef would thus interrupt the expected smooth line intersection marked by the potash occurrence.

Selected Bibliography

- 1 Alger, R. P. and E. R. Crain, 1965, DEFINING EVAPORITE DEPOSITS WITH ELECTRICAL WELL LOGS, Northern Ohio Geological Society Second Symposium on Salt, p. 116-130.
- 2 Alling, H. L. and L. I. Briggs, Jr., 1961, STRATIGRAPHY OF UPPER SILURIAN CAYUGAN EVAPORITES, American Association of Petroleum Geologists Bulletin, v. 45, p. 515-547.
- 3 Anderson, R. J., and G. C. Egelson, 1970, DISCOVERY OF POTASH IN THE A-1 SALINA SALT IN MICHIGAN, In; SIXTH FORUM ON GEOLOGY OF INDUSTRIAL MINERALS, Michigan Geological Survey Miscellany 1, p. 15-19.

- 4 _____, and E. C. Majeske, 1970, DETECTION OF POTASH ZONES BY DRILLING FLUID ANALYSIS, In; SIXTH FORUM ON GEOLOGY OF INDUSTRIAL MINERALS, Michigan Geological Survey Miscellany 1, p. 34-36.
- 5 Bolton, T. E., and B. A. Liberty, 1955, SILURIAN STRATIGRAPHY OF THE NIAGARAN ESCARPMENT, ONTARIO, Michigan Geological Society Annual Field Trip, p. 19-38.
- 6 Borchert, H., 1963, DEPOSITION OF ANCIENT SALT DEPOSITS WITH PARTICULAR REFERENCE TO METASOMATISM, Geological Society of America Special Paper 73, abstract, p. 271.
- 7 _____, and R. O. Muir, 1964, SALT DEPOSITS - THE ORIGIN, METAMORPHISM, AND DEFORMATION OF EVAPORITES, VanNostrand: London, England, p.338.
- 8 Braitsch, O., 1971, SALT DEPOSITS - THEIR ORIGIN AND COMPOSITION, Translated by P. J. Burek and A. E. M. Nairn, Springer-Verlog: New York, p. 297.
- 9 Branson, E. B., 1915, ORIGIN OF THICK GYPSUM AND SALT DEPOSITS, Geological Society of America Bulletin, v. 26, p. 231-242.
- 10 Briggs, L. I., 1957, QUANTITATIVE ASPECTS OF EVAPORITE DEPOSITION, Michigan Academy of Science, Arts, and Letters Papers, v. 42, p. 115-123.
- 11 _____, 1958, EVAPORITE FACIES, Journal of Sedimentary Petrology, v. 28, p. 46-56.
- 12 _____, 1963, DEPOSITION OF EVAPORITES IN THE MICHIGAN BASIN, In; SYMPOSIUM ON SALT, Northern Ohio Geological Society, abstract, p. 55.
- 13 _____, and D. Briggs, 1974, NIAGARA-SALINA RELATIONSHIPS IN THE MICHIGAN BASIN, In; SILURIAN REEF-EVAPORITE RELATIONSHIP, Michigan Basin Geological Society 1974 Field Conference, p. 1-23.
- 14 _____, and P. T. Lucas, 1954, MECHANICS OF SALINA SALT DEPOSITION IN THE MICHIGAN BASIN, Geological Society of America Bulletin, abstract, v. 65, p. 1233.
- 15 _____, and H. N. Pollack, 1967, DIGITAL MODEL OF EVAPORITE SEDIMENTATION, Science, v. 155, no. 3761, p. 453-456.
- 16 Chute, N. E., 1972, SUBSURFACE STRATIGRAPHY AND STRUCTURE NEAR THE MORTON SALT COMPANY'S MINE ON SENECA LAKE, NEW YORK, Geological Society of America Abstracts with Programs, v. 4, p. 9-10.
- 17 Cramer, H. R., 1969, EVAPORITES, In; A SELECTED BIBLIOGRAPHY, American Association of Petroleum Geologists Bulletin, v. 53, no. 4, p. 982-1011.
- 18 Dellwig, L. F., 1953, HOPPER CRYSTALS OF HALITE IN THE SALINA OF MICHIGAN, American Mineralogist, v. 38, p. 730-731.
- 19 _____, 1955, ORIGIN OF THE SALINA SALT OF MICHIGAN, Journal of Sedimentary Petrology, v. 25, no. 2, p. 83-110.
- 20 _____, and L. I. Briggs, Jr., 1952, TEXTURAL RELATIONSHIPS IN THE SALINA SALT OF MICHIGAN, Geological Society of America Bulletin, abstract, v. 63, p. 1242; also in American Mineralogist, v. 38, p. 334.
- 21 _____, and R. Evans, 1969, DEPOSITIONAL PROCESSES IN SALINA SALT OF MICHIGAN, OHIO AND NEW YORK, American Association of Petroleum Geologists Bulletin, v. 53, p. 949-956.
- 22 Ehlers, G. M., 1945, STRATIGRAPHY OF THE SURFACE FORMATIONS, In; GEOLOGY OF THE MACKINAC STRAITS REGION AND SUBSURFACE GEOLOGY OF NORTHERN SOUTHERN PENINSULA, Landes, K. K., et al., Michigan Geological Survey Publication 44, Geological Series 37, p. 19-120.
- 23 _____, and R. V. Kesling, 1957, SILURIAN ROCKS OF THE NORTHERN PENINSULA OF MICHIGAN, Michigan Geological Society Annual Geological Excursion.
- 24 _____, _____, 1962, SILURIAN ROCKS OF MICHIGAN AND THEIR CORRELATION, In; SILURIAN ROCKS OF THE SOUTHERN LAKE MICHIGAN AREA, Michigan Basin Geological Society Annual Field Conference, Michigan Geological Survey, p. 1-20.

- 25 Ellis, G. D., 1958,
NOTES ON THE DEVONIAN-SILURIAN IN
THE SUBSURFACE OF SOUTHWEST
MICHIGAN,
Michigan Geological Survey Progress
Report 18.
- 26 _____, 1962,
SILURIAN ROCKS IN THE SUBSURFACE OF
SOUTHERN MICHIGAN, In; SILURIAN ROCKS
OF THE SOUTHERN LAKE MICHIGAN AREA,
Michigan Basin Geological Society Annual
Field Conference, Michigan Geological
Survey Division, p. 39-49.
- 27 _____, 1964,
MICHIGAN'S SILURIAN REEFS ENHANCE
WIDESPREAD AREAS,
World Oil, v. 159, no. 5, p. 155-158.
- 28 _____, 1967,
MICHIGAN'S SILURIAN OIL AND GAS POOLS,
Michigan Geological Survey Report of
Investigation 2.
- 29 _____, 1969,
ARCHITECTURE OF THE MICHIGAN BASIN,
In; STUDIES OF THE PRECAMBRIAN OF THE
MICHIGAN BASIN,
Michigan Basin Geological Society Annual
Field Excursion Guidebook, p. 60-88.
- 30 Evans, C. S., 1950,
UNDERGROUND HUNTING IN THE
SILURIAN OF SOUTHWESTERN ONTARIO,
Geological Association of Canada
Proceedings, v. 3, p. 55-85.
- 31 Garrett, D. E., 1966,
THE CHEMISTRY AND ORIGIN OF POTASH
DEPOSITS,
American Chemical Society Annual
Meeting 152, manuscript no. 66-487,
unpublished.
- 32 Gary, M., R. McAfee, Jr., and C. L. Wolf
(Editors), 1974,
GLOSSARY OF GEOLOGY,
American Geological Institute: Washington,
D. C.
- 33 Gill, D., 1977,
THE BELLE RIVER MILLS GAS FIELD;
PRODUCTIVE NIAGARAN REEFS ENCASED
BY SABKHA DEPOSITS, MICHIGAN BASIN,
Michigan Basin Geological Society, Special
Papers #2.
- 34 _____, 1979,
DIFFERENTIAL ENTRAPMENT OF OIL AND
GAS IN NIAGARAN PINNACLE-REEF BELT
OF NORTHERN MICHIGAN,
American Association of Petroleum
Geologists Bulletin, v. 63, no. 4, p. 608-620.
- 35 Goldsmith, L. H., 1966,
SOME FUNDAMENTALS OF POTASH
GEOLOGY AS A GUIDE TO EXPLORATION IN
HOUSTON, TEXAS,
Society of Professional Well Log Analysts,
7th Annual Logging Symposium
Transactions.
- 36 _____, 1969,
CONCENTRATION OF POTASH SALTS IN
SALINE BASINS,
American Association of Petroleum
Geologists Bulletin, v. 53, no. 4, p. 790-797.
- 37 Gordon, W. A., 1975,
DISTRIBUTION BY LATITUDE OF
PHANEROZOIC EVAPORITE DEPOSITS,
The Journal of Geology, v. 83, no. 6,
p. 671-684.
- 38 Grabau, A. W., 1913,
THE ORIGIN OF SALT DEPOSITS WITH
SPECIAL REFERENCE TO THE SILURIC SALT
DEPOSITS OF NORTH AMERICA,
Mining and Metallurgy Society of America
Bulletin, v. 6, no. 2, [no. 57], p. 34-44.
- 39 _____, 1915,
MINERAL RESOURCES OF MICHIGAN WITH
STATISTICAL TABLES OF PRODUCTION AND
VALUE OF MINERAL PRODUCTS FOR 1914
AND PRIOR YEARS: WITH A TREATISE ON
MICHIGAN COPPER DEPOSITS, In;
NON-METALLIC MINERALS,
Michigan Geological and Biological Survey,
Publication 19, Geological Series 16, Pt 2,
p. 325.
- 40 Greensmith, J. T., 1957,
THE STATUS AND NOMENCLATURE OF
STRATIFIED EVAPORITES,
American Journal of Science, v. 255,
p. 593-595; Discussion, op. cit., v. 256,
p. 219-220, 525.
- 41 Hite, R. J., 1961,
POTASH-BEARING EVAPORITE CYCLES IN
THE SALT ANTICLINES OF THE PARADOX
BASIN, COLORADO AND UTAH,
United States Geological Survey
Professional Paper 424-D, p. D135-D138.
- 42 _____, 1973,
SHELF CARBONATE SEDIMENTATION
CONTROLLED BY SALINITY IN THE
PARADOX BASIN, SOUTHEAST UTAH, In;
MARINE EVAPORITES, ORIGIN, DIAGENESIS
AND GEOCHEMISTRY,
Kirkland, D. W. and R. Evans (Editors),
Dowden, Hutchinson & Ross, Inc.:
Stroudsburg, Pennsylvania, p. 147-165.
- 43 _____, and W. C. Gere, 1958,
POTASH DEPOSITS OF THE PARADOX
BASIN, In; GUIDEBOOK TO THE GEOLOGY OF
THE PARADOX BASIN,
Intermountain Association of Petroleum
Geologists 9th Annual Field Conference,
p. 221-225.
- 44 Holser, W. T., 1966,
BROMIDE GEOCHEMISTRY OF SALT ROCKS,
In; SECOND SYMPOSIUM ON SALT,
Northern Ohio Geological Society, v. 1,
p. 248-275.
- 45 Huh, J. M., L. I. Briggs, and D. Gill, 1978,
DEPOSITIONAL ENVIRONMENTS OF
PINNACLE REEFS, NIAGARA AND SALINA
GROUPS, NORTHERN SHELF, MICHIGAN
BASIN, In; REEFS AND EVAPORITES -
CONCEPTS AND DEPOSITIONAL MODELS,
American Association of Petroleum
Geologists, Studies in Geology, no. 5,
p. 1-21.
- 46 Johnson, A. M., et al., 1979,
THE MAPLE BLOCK KNOLL REEF IN THE
BUSH BAY DOLOSTONE (SILURIAN,
ENGADINE GROUP), NORTHERN
PENINSULA OF MICHIGAN,
Museum of Paleontology Papers on
Paleontology no. 20, Ann Arbor, Michigan.
- 47 Johnson, K. S., and S. Gonzales, 1976,
GEOLOGY AND SALT DEPOSITS OF THE
MICHIGAN BASIN,
Prepared for Union Carbide Corporation,
Nuclear Division, Office of Waste Isolation
Y/OWI/SUB.-4494/2.
- 48 _____, _____, 1978,
SALT DEPOSITS IN THE UNITED STATES
AND REGIONAL GEOLOGIC
CHARACTERISTICS IMPORTANT FOR
STORAGE OF RADIOACTIVE WASTE,
Prepared for Union Carbide Corporation,
Nuclear Division, Office of Waste Isolation
Y/OWI/SUB.-7414/1, p. 13-38.
- 49 Jones, C. L., 1959,
POTASH DEPOSITS IN THE CARLSBAD
REGION, SOUTHEASTERN NEW MEXICO,
Economic Geology, abstract, v. 54, p. 1349;
also in Geological Society of America
Bulletin, v. 70, p. 1625.
- 50 Kaufmann, D. W. and C. B. Slawson, 1950,
RIPPLE MARK IN ROCK SALT OF THE
SALINA FORMATION,
Journal of Geology, v. 58, p. 24-29.
- 51 Kay, M., 1955,
SEDIMENTS AND SUBSIDENCE THROUGH
TIME, IN THE CRUST OF THE EARTH,
Geological Society of America Special
Paper 62, p. 665-684.
- 52 Keys, D. A. and J. Y. Wright, 1966,
GEOLOGY OF THE I.M.C. POTASH DEPOSIT
ESTERHAZY, SASKATCHEWAN, In;
NORTHERN OHIO GEOLOGICAL SOCIETY
2ND SYMPOSIUM ON SALT,
Northern Ohio Geological Society,
p. 95-101.
- 53 Kinsman, D. J. J., 1969,
MODES OF FORMATION, SEDIMENTARY
ASSOCIATIONS, AND DIAGNOSTIC
FEATURES OF SHALLOW WATER AND
SUPRATIDAL EVAPORITES,
American Association of Petroleum
Geologists Bulletin, v. 53, p. 830-840.
- 54 Klingspor, A. M., 1966,
CYCLIC DEPOSITS OF POTASH IN
SASKATCHEWAN,
Canadian Petroleum Geology Bulletin,
v. 14, p. 193-207.
- 55 _____, 1969,
MIDDLE DEVONIAN MUSKEG EVAPORITES
OF WESTERN CANADA,
American Association of Petroleum
Geologists Bulletin, v. 53, no. 4, p. 927-948.
- 56 Kozary, M. T., J. C. Dunlap, and W. E.
Humphrey, 1968,
INCIDENCE OF SALINE DEPOSITS IN
GEOLOGIC TIME,
Geological Society of America Special
Paper 88, p. 43-57.
- 57 Kroenlein, G. A., 1939,
SALT, POTASH, AND ANHYDRITE IN
CASTILE FORMATION OF SOUTHEAST NEW
MEXICO,
American Association of Petroleum
Geologists Bulletin, v. 23, p. 1682-1693.
- 58 Krumbein, W. C., 1951,
OCCURRENCE AND LITHOLOGIC
ASSOCIATIONS OF EVAPORITES IN THE
UNITED STATES,
Journal of Sedimentary Petrology, v. 21,
p. 63-81.
- 59 _____, and R. M. Garrels, 1952,
ORIGIN AND CLASSIFICATION OF
CHEMICAL SEDIMENTS IN TERMS OF PH
AND OXIDATION-REDUCTION POTENTIALS,
Journal of Geology, v. 60, p. 1-33.
- 60 Kunasz, I. A., 1968,
SIGNIFICANCE OF LAMINATIONS IN THE
UPPER SALINA SALT OF THE MICHIGAN
BASIN,
Master of Science Thesis, Pennsylvania
State University, Harrisburg, Pennsylvania.
- 61 Landes, K. K., 1945,
THE SALINA AND BASS ISLANDS ROCKS IN
THE MICHIGAN BASIN,
United States Geological Survey
Preliminary Map 40, Oil and Gas
Investigation Series.
- 62 _____, 1951,
ORIGIN OF THICK-BEDDED SALT DEPOSITS
Economic Geology, abstract, v. 46,
p. 798-799, Geological Society of America
Bulletin, v. 62, p. 1457.
- 63 _____, 1963,
ORIGIN OF SALT DEPOSITS, In; SYMPOSIUM
ON SALT: CLEVELAND, OHIO,
Northern Ohio Geological Society, p. 3-9.

- 64 _____, 1972,
POSSIBLE SALT MINE SITES FOR
RADIOACTIVE-WASTE DISPOSAL IN THE
NORTHEASTERN STATES,
Prepared for Union Carbide Corporation,
Nuclear Division, Oak Ridge National
Laboratory, ORNL/SUB-3733/1.
- 65 _____, and H. L. Bourne, 1976,
POSSIBLE SALT MINE AND BRINED CAVITY
SITES FOR RADIOACTIVE-WASTE DISPOSAL
IN THE NORTHEASTERN SOUTHERN
PENINSULA OF MICHIGAN (2ND EDITION),
Prepared for Union Carbide Corporation,
Nuclear Division, Oak Ridge National
Laboratory, ORNL/SUB.-7010/1.
- 66 Lang, W. T. B., 1957,
ANNOTATED BIBLIOGRAPHY AND INDEX
MAP OF SALT DEPOSITS IN THE UNITED
STATES,
United States Geological Survey Bulletin
1019-J, p. 715-753.
- 67 Leford, S. J., 1969,
HANDBOOK OF WORLD SALT RESOURCES,
Plenum Press: New York, New York.
- 68 Lowenstam, H. A., 1950,
NIAGARAN REEFS OF THE GREAT LAKES
AREA,
Journal of Geology, v. 58, p. 430-487.
- 69 _____, 1957,
NIAGARAN REEFS OF THE GREAT LAKES
AREA,
Geological Society of America Memoir 67,
v. 1, p. 215-248.
- 70 Lucas, P. T., 1954,
ENVIRONMENTS OF SALINA SALT
DEPOSITION,
Master of Science Thesis, University of
Michigan, Ann Arbor, Michigan.
- 71 Mantek, W., 1973,
NIAGARAN PINNACLE REEFS IN
MICHIGAN, In: GEOLOGY AND THE
ENVIRONMENT; MAN, EARTH, AND
NATURE IN NORTHWESTERN LOWER
MICHIGAN,
Michigan Basin Geological Society, Annual
Field Excursion, p. 35-46.
- 72 Martinez, J. D., 1974,
TECTONIC BEHAVIOR OF EVAPORITES, In;
FOURTH SYMPOSIUM ON SALT, Coogan, A.
H., (Editor),
Northern Ohio Geological Society, v. 1, p.
155-168.
- 73 Matthews, R. D., 1970,
THE DISTRIBUTION OF SILURIAN POTASH
IN THE MICHIGAN BASIN, In; SIXTH FORUM
ON GEOLOGY OF INDUSTRIAL MINERALS,
Michigan Geological Survey Miscellany 1,
p. 20-33.
- 74 _____, and G. C. Egleson, 1974,
ORIGIN AND IMPLICATIONS OF A
MID-BASIN POTASH FACIES IN THE SALINA
SALT OF MICHIGAN, In; FOURTH
INTERNATIONAL SYMPOSIUM ON SALT,
Northern Ohio Geological Society, v. 1,
p. 15-34.
- 75 Melhorn, W. N., 1958,
STRATIGRAPHIC ANALYSIS OF SILURIAN
ROCKS IN MICHIGAN BASIN,
American Association of Petroleum
Geologists Bulletin, v. 42, no. 4, p. 816-838.
- 76 Mesolella, K. J., et al., 1974,
CYCLIC DEPOSITION OF SILURIAN
CARBONATES AND EVAPORITES IN
MICHIGAN BASIN,
American Association of Petroleum
Geologists Bulletin, v. 58, no. 1, p. 34-62.
- 77 Netherland, S. and Associates, Inc., 1975,
PRELIMINARY REGIONAL STUDY OF THE
PRESENT AND POSSIBLE FUTURE OIL AND
GAS DEVELOPMENT IN THE AREAS OF
THICK ROCK SALT AND SHALE DEPOSITS
OF MICHIGAN, OHIO, PENNSYLVANIA AND
WESTERN NEW YORK AS OF DECEMBER,
1975,
Prepared for Union Carbide Corporation,
Nuclear Division, Oak Ridge National
Laboratory, ORNL/SUB-75/ 87989.
- 78 Newcombe, R. B., 1933,
OIL AND GAS FIELDS OF MICHIGAN,
Michigan Geological Survey Publication 38,
Geological Series 32.
- 79 Nurmi, R. D. and G. M. Friedman, 1977,
SEDIMENTOLOGY AND DEPOSITIONAL
ENVIRONMENTS OF BASIN-CENTER
EVAPORITES, LOWER SALINA GROUP
(UPPER SILURIAN), MICHIGAN BASIN, In;
REEFS AND EVAPORITES-CONCEPTS AND
DEPOSITIONAL MODELS,
American Association of Petroleum
Geologists, Studies in Geology no. 5,
p. 23-52.
- 80 Pannekoek, A. J., 1965,
SHALLOW-WATER AND DEEP-WATER
EVAPORITE DEPOSITION,
American Journal of Science, v. 263,
p. 284-285.
- 81 Pierce, W. G., and E. I. Rich, 1962,
SUMMARY OF THE ROCK SALT DEPOSITS IN
THE UNITED STATES AS POSSIBLE STORAGE
SITES FOR RADIOACTIVE WASTE
MATERIALS,
United States Geological Survey Bulletin
1148.
- 82 Prouty, C. E., 1976,
IMPLICATIONS OF IMAGERY STUDIES TO
TIME AND ORIGIN OF MICHIGAN BASIN
LINEAR STRUCTURES,
American Association of Petroleum
Geologists Bulletin, abstract, v. 60, p. 709.
- 83 Raup, P. B., 1970,
BRINE MIXING: AN ADDITIONAL
MECHANISM FOR FORMATION OF BASIN
EVAPORITES,
American Association of Petroleum
Geologists Bulletin, v. 54, p. 2246-2259.
- 84 Raymer, L. L. and W. P. Biggs, 1963,
MATRIX CHARACTERISTICS DEFINED BY
POROSITY COMPUTATIONS,
Transactions of Society of Professional
Well Log Analysts Meeting 1963, p. X-12
through X-20.
- 85 Rickard, L. V., 1966,
GAMMA RAY LOGS AND THE ORIGIN OF
SALT, In; THIRD SYMPOSIUM ON SALT,
The Northern Ohio Geological Society,
Inc., Cleveland, Ohio, p. 34-39.
- 86 _____, 1969,
STRATIGRAPHY OF THE UPPER SILURIAN
SALINA GROUP, NEW YORK,
PENNSYLVANIA, OHIO, ONTARIO,
New York State Museum and Science
Service, Map and Chart Series 12.
- 87 Roliff, W. A., 1949,
SALINA-GUELPH FIELDS IN
SOUTHWESTERN ONTARIO,
American Association of Petroleum
Geologists Bulletin, v. 33, no. 2, p. 153-188.
- 88 Sandberg, C. A., 1973,
SALT AND POTASH, In; MINERAL AND
WATER RESOURCES OF NORTH DAKOTA,
United States Congress 93rd, 1st Session,
Senate Committee, Interior and Insular
Affairs, (Also North Dakota Geological
Survey Bulletin 63), p. 140-151.
- 89 Sanford, B. V., 1965,
SALINA SALT BEDS-SOUTHWESTERN
ONTARIO,
Geological Survey of Canada, Paper 65-9.
- 90 _____, and W. B. Brady, 1955,
PALEOZOIC GEOLOGY OF THE
WINDSOR-SARNIA AREA, ONTARIO,
Canada Department of Mines and
Technical Surveys, Geological Survey of
Canada Memoir 278.
- 91 Sargent, E. H. & Company, 1964
PERIODIC TABLE OF THE ELEMENTS,
Chicago, Illinois
- 92 Schlumberger Limited, 1972,
LOG INTERPRETATION,
Principles, v. 1, p. 108.
- 93 Schmalz, R. F., 1966a,
ENVIRONMENTS OF MARINE EVAPORITE
DEPOSITION,
Mineral Industries, v. 35, no. 8, p. 1-7.
- 94 _____, 1966b,
EVAPORITE DEPOSITION IN A
THERMODYNAMICALLY OPEN SYSTEM
(SUMMARY),
11th Pacific Science Congress Proceedings,
Chemical and Biological Oceanography
Section, v. 2, p. 12.
- 95 _____, 1969,
DEEP-WATER EVAPORITE DEPOSITION: A
GENETIC MODEL,
American Association of Petroleum
Geologists Bulletin, v. 53, no. 4, p. 798-823.
- 96 Schwerdtner, W. M., 1964,
GENESIS OF POTASH ROCKS IN MIDDLE
DEVONIAN PRAIRIE EVAPORITE
FORMATION OF SASKATCHEWAN,
American Association of Petroleum
Geologists Bulletin, v. 48, p. 1108-1115.
- 97 Scruton, P. C., 1953,
DEPOSITION OF EVAPORITES,
American Association of Petroleum
Geologists Bulletin, v. 37, p. 2498-2512.
- 98 Sharma, G. D., 1966,
GEOLOGY OF PETERS REEF, ST. CLAIR
COUNTY, MICHIGAN,
American Association of Petroleum
Geologists Bulletin, v. 50, no. 2, p. 327-350.
- 99 Shaver, R. H., 1977,
SILURIAN REEF GEOMETRY-NEW
DIMENSIONS TO EXPLORE,
Journal of Sedimentary Petrology, v. 47,
no. 4, p. 1409-1424.
- 100 _____, and J. B. Droste, 1977,
SYNCHRONIZATION OF DEPOSITION:
SILURIAN REEF-BEARING ROCKS ON
WABASH PLATFORM WITH CYCLIC
EVAPORITES OF MICHIGAN BASIN,
American Association of Petroleum
Geologists, Reprinted from Studies in
Geology no. 5.
- 101 Shearman, D. J., 1973,
ORIGIN OF MARINE EVAPORITES BY
DIAGENESIS, In; MARINE EVAPORITES:
ORIGIN, DIAGENESIS AND GEOCHEMISTRY,
Kirkland, D. W. and R. Evans, (Editors),
Dowden, Hutchinson & Ross, Inc.:
Stroudsburg, Pennsylvania, p. 61-68
- 102 Shelden, F. D., 1963,
TRANSGRESSIVE MARGINAL LITHOTOPES
IN NIAGARAN (SILURIAN) OF NORTHERN
MICHIGAN BASIN,
American Association of Petroleum
Geologists Bulletin, v. 47, no. 1, p. 129-149.

- 103 Sloss, L. L., 1953,
THE SIGNIFICANCE OF EVAPORITES,
Journal of Sedimentary Petrology, v. 23,
p. 143-161.
- 104 _____, 1969,
EVAPORITE DEPOSITION FROM LAYERED
SOLUTIONS,
American Association of Petroleum
Geologists Bulletin, v. 53, p. 776-789.
- 105 Smith, H. L., 1938,
POTASH IN THE PERMIAN SALT BASIN,
Industry and Engineering Chemistry,
Industry Edition, v. 30, p. 854-860.
- 106 Smith, R. A., 1914,
NON-METALLIC MINERALS, In; MINERAL
RESOURCES OF MICHIGAN WITH
STATISTICAL TABLES OF PRODUCTION AND
VALUE OF MINERAL PRODUCTS FOR 1914
AND PRIOR YEARS; WITH A TREATISE ON
MICHIGAN COPPER DEPOSITS,
Michigan Geological and Biological Survey
Publication 19, Geological Series 16, pt. 2,
p. 245-329.
- 107 Stanton, Jr., R. J., 1966,
THE SOLUTION BRECCIATION PROCESS,
Geological Society of America Bulletin,
v. 77, no. 8, p. 843-848.
- 108 Stewart, F. H., 1963,
MARINE EVAPORITES, CHAPTER Y, In; DATA
OF GEOCHEMISTRY-6th EDITION,
United States Geological Survey
Professional Paper 440-Y, p. Y1-Y52.
- 109 Swartz, C. K., et al., 1942,
CORRELATION OF THE SILURIAN
FORMATIONS OF NORTH AMERICA,
Geological Society of America Bulletin,
v. 53, p. 533-538.
- 110 Trusheim, F., 1960,
MECHANISM OF SALT MIGRATION IN
NORTHERN GERMANY,
American Association of Petroleum
Geologists Bulletin, v. 44, no. 9,
p. 1519-1540.
- 111 Ulteig, J. R., 1964,
UPPER NIAGARAN AND CAYUGAN
STRATIGRAPHY OF NORTHEASTERN OHIO
AND ADJACENT AREAS,
Ohio Geological Survey Report of
Investigation 51.
- 112 Valyashko, M. G., 1956,
GEOCHEMISTRY OF BROMINE IN THE
PROCESSES OF SALT DEPOSITION AND USE
OF THE BROMINE CONTENT AS A GENETIC
AND PROSPECTING CRITERION,
Geochemistry (translated from Russian),
no. 6, p. 570-589.
- 113 Vanderwilt, J. W., 1923,
A DRILL CORE SECTION OF THE SALINA
BELOW THE SALT BED OF THE DETROIT
ROCK SALT COMPANY MINE,
Papers of the Michigan Academy of
Science Arts and Letters, v. 3, p. 285-287.
- 114 Weaver, P., 1946,
THE FORMATION OF EVAPORITES UNDER
MARINE EVAPORATION CONDITIONS,
Oil Weekly, abstract, v. 123, no. 8, p. 33;
also in American Association of Petroleum
Geologists Bulletin, v. 39, p. 1965-1966.
- 115 Wilmarth, M. G., 1938,
LEXICON OF GEOLOGIC NAMES OF THE
UNITED STATES (INCLUDING ALASKA),
United States Government Printing Office,
Washington, D.C., Bulletin 896, pt. 2, M-Z.
- 116 Zen, E., 1959,
EARLY STAGES OF EVAPORITE DEPOSITION
Geological Society of America Bulletin,
abstract, v. 70, p. 1704.
- 117 _____, 1960,
EARLY STAGES OF EVAPORITE DEPOSITION,
United States Geological Survey
Professional Paper 400-B, p. B458-B461.

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