

Origin and Implications of a Mid-Basin Potash Facies in the Salina Salt of Michigan

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ABSTRACT

Sylvinite, a mixture of sylvite (KCl) and halite (NaCl) was discovered in A-1 Salt (Salina Group, Cayugan age) by Anderson and Egleson in a Dow Chemical Company salt core late in 1966. The potash zone, 92 feet thick in the Midland core, contained potassium values, as K_2O , up to 40%. The total potash-bearing zone averaged about 4% K_2O . Neither magnesium nor sulfate is present in appreciable amounts.

New subsurface data and continuing geological studies have confirmed the authors' original (1967) conclusions - (1) Sylvinite underlies some 13,000 square miles of the Michigan Basin, (2) the potash facies occurs as a lense within a lense of halite, (3) the potash deposit increases in thickness and purity basin-ward, (4) cooling was a factor in the crystallization of the potassium chloride, (5) large volumes of potassium salts were deposited only during the first evaporite megacycle, (6) sea level fluctuation was the principle factor in controlling the evaporite megacycles, (7) periods of lowest water over the basin rims are marked by wide-spread clastics within the evaporite sequence, (8) the potash deposition in mid-basin occurred at a time when the basin and the approaches to the basin were water-covered, and (9) the thickness and relative purity of the A-1, A-2, and lower B Salts are best explained by the inertia of a large mass of brine found only in a deep basin.

The bromine content of halite increases from the base of the A-1 Salt to maximum values in and above the potash zone, clear evidence of a gradual change in density in the parent brine during the concentration phase of the A-1 megacycle. In addition, the average bromine content decreases vertically in the salt above the potash zone; bromine profiles from widely spaced wells show this evidence of a gradual dilution phase as the A-1 megacycle drew to a close. The distribution of bromine through 450 vertical feet of relatively pure A-1 Salt and the absence of unconformity at

the stratigraphic position of the potash denies a shallow-water origin for the early evaporites in mid-basin.

INTRODUCTION

Prior Dow work

The geochemical evidence which in 1966 led to the finding of colorless sylvite in a Dow Chemical Company salt core was described in 1970 by the discoverers, Anderson and Egleson and also by other Dow workers (Anderson and Majeske, 1970; Anderson, Egleson, Matthews and Majeske, 1972). Two papers discussing the extent of the potash deposit, and its postulated origins were published by Matthews (1970a, 1970b). The early geological studies were initially limited to a single evaporite megacycle known to contain a new evaporite lithofacies. Other evaporite megacycles of the Salina Group and the Devonian-Detroit River Group have since been investigated.

New subsurface data from deep drilling in Michigan and continuing geological studies of the potash deposits have confirmed the authors' original (1967) conclusions: (1) sylvinite underlies some 13,000 square miles (33,800 km^2) of the Michigan Basin, (2) the potash facies occurs as a lense within a lense of halite, (3) the potash deposit increases in thickness and purity basin-ward, (4) cooling was a factor in the crystallization of the potassium chloride, (5) large volumes of potassium salts were deposited in mid-basin only during the first evaporite megacycle, (6) sea level fluctuation was the principle factor in controlling the evaporite megacycles, (7) periods of lowest water over the basin rims are marked by widespread allochthonous clays and other clastics within the evaporite sequence, and (8) the potash deposition in mid-basin occurred at a time when the basin and the approaches to the basin were largely watercovered.

Problems considered

The presence of 13,000 square miles (33,800 km²) of bedded potash in mid-basin requires a re-examination of evaporite depositional theories as applied to the Michigan Basin. Previous references to bittern salts were based on trace amounts (Lucas, 1954; Dellwig, 1955), the quantities which now must be explained are major. Why potash only in the lowest salt? Why in a mid-position in that salt? Why are clastics common in the upper salts and rare in the lower, thicker salt where the potash occurs? Can the potash be associated with deep-basin halite? In considering these questions, we will review some of the analytical data relating to potash and the evidence bearing on its distribution in Michigan. We will then discuss briefly some of the basic premises concerning evaporite deposition and conclude with a suggested depositional history for the Michigan Salina Group.

POTASH IN MICHIGAN

Analytical data from Dow #8 core

Location and terminology. The Dow Chemical Company's #8 Salt well at Midland, Michigan (Sec. 21, T14N-R2E) was cored through several of the Salina salts (Fig. 1). The terminology of the Salina Group is shown by the gamma ray log of a well (Good & Good #GG-1 Thom, Sec. 10, T8N-R9E) located beyond the limits of mid-basin potash facies (Fig. 2).

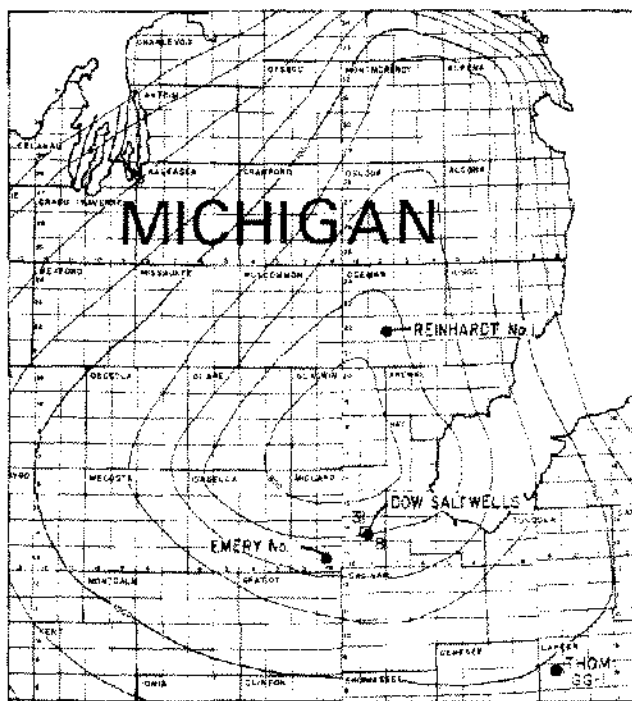


Figure 1. Aggregate thickness of salt in Salina Group (Landes, 1945), with well locations.

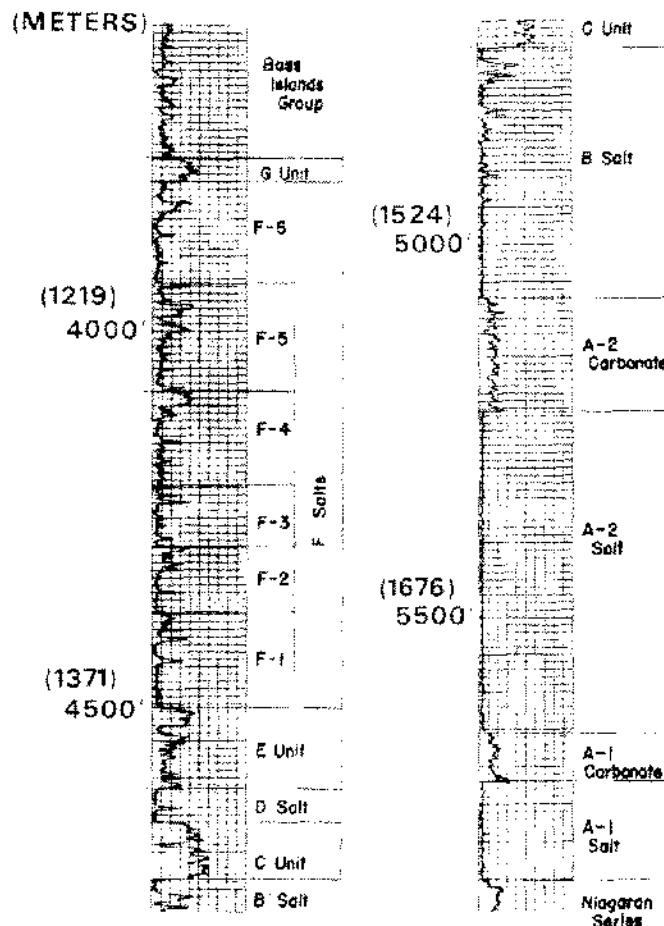


Figure 2. Michigan Salina terminology. Typical gamma-ray log beyond the limits of the potash (Good and Good, GG-1 Thom, Sec. 10, T8N-R9E, Lapeer County) (Matthews, 1970a).

Potassium values. The salt core was analyzed for potassium and bromine by X-ray fluorescence. The potassium values as K₂O ranged from less than 0.5% to more than 40%. Figures 3, 4, and 5 give the concentration of potash found in three sections of the Dow well where it is most prevalent. In some of the sections the diameter of the core was reduced by dissolving action of the drilling fluid. In a few places, inches, or even feet, of core were missing, but it is probably safe to assume that these missing sections would be relatively high in potash. The locations of the incomplete cores are indicated on the graphs. Assuming 25% K₂O as indicated in these charts, the 92-foot (18.6 m) interval between 8,295 (2,489 m) and 8,387 (2,515 m) feet averages just over 4% K₂O (Anderson and Egieson, 1970).

Potassium and Bromine. The bromine content of potassium chloride was found to increase as the percentage of potassium chloride decreases in the sylvinite mix-

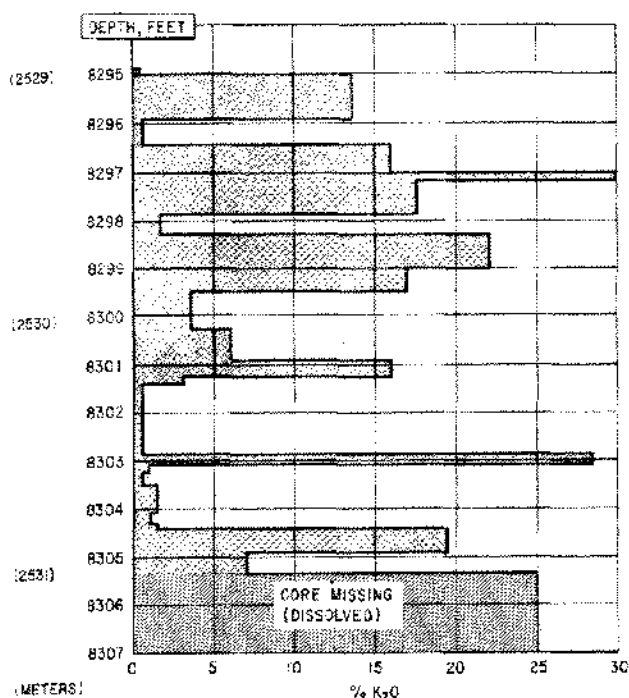


Figure 3. Potash in salt core from Dow #8 Salt (upper section of the core) (Anderson and Egleson, 1970.)

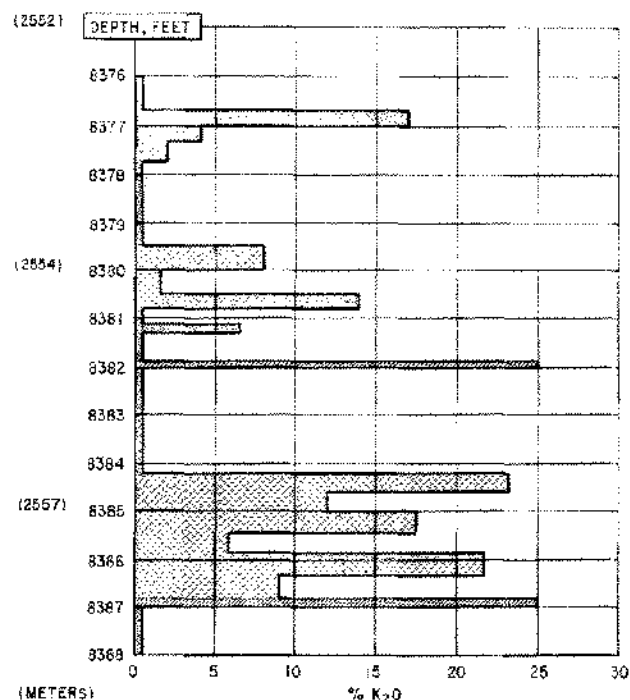


Figure 5. Potash in salt core from Dow #8 Salt (lower section of the core) (Anderson and Egleson, 1970.)

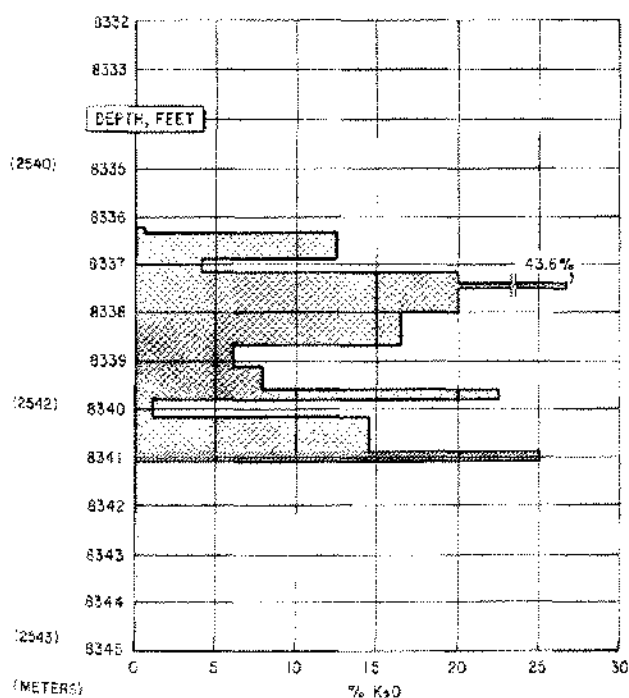


Figure 4. Potash in salt core from Dow #8 Salt (middle section of the core) (Anderson and Egleson, 1970.)

ture (Fig. 6). Potassium analyses were compared with these for bromine in a number of samples. Two samples with a bromine content as low as 210 ppm contained 2 or 3% K, although K was generally absent when the bromine was less than 300 ppm. In only one sample with a bromine content greater than 400 ppm was it impossible to detect any K.

At low concentrations of potassium chloride, say 2%, in the sylvinite mixture, the bromine content of the KCl is about 4300 ppm. At high concentrations of potassium chloride, say 75% KCl, the bromine content of the KCl is about 2100 ppm.

According to Braitsch (1965) this indicates that cooling played an important part in the crystallization of the potassium chloride. He reports that the first sylvinite crystallized at 0°C contains about 2400 ppm Br, while that crystallized at 50°C contains about 3600 ppm Br.

Bromine was analyzed in both sylvinite (KCl) and halite (NaCl) where the two minerals were physically mixed. The ratios of bromine in sylvinite over bromine in halite are 15 or 20 to 1, instead of the classical 10 to 1 (Fig. 7). This indicates the halite associated with sylvinite precipitated from a less concentrated brine than did the sylvinite. We believe the NaCl could have been derived from warm surface brines, while the bulk of the KCl was crystallizing

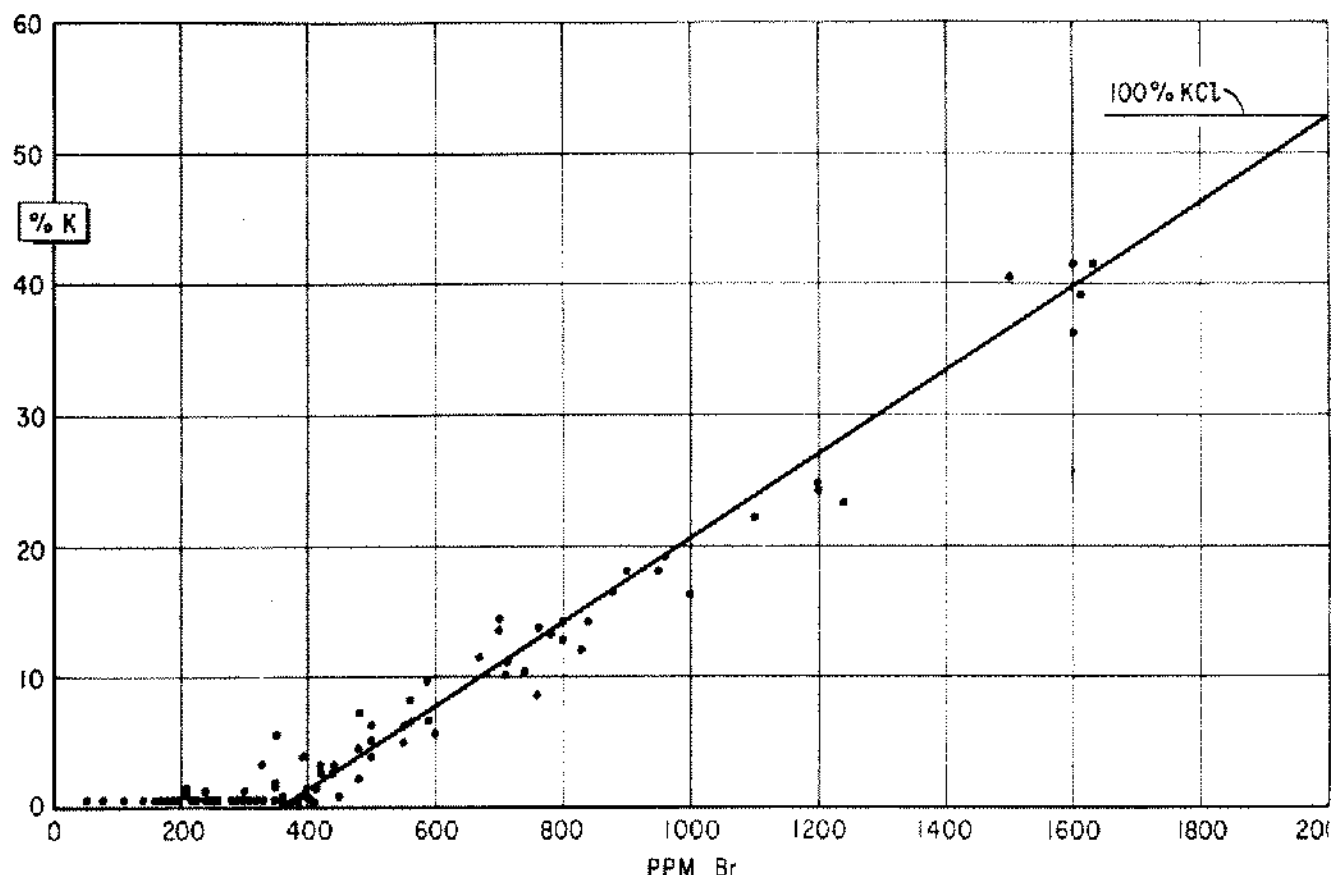


Figure 6. Potassium vs. bromine in salt core from Dow #8 Salt (Anderson and Egleson, 1970).

	8283'3"- 8294'3"	8'296'5"- 8297'0"	8337'0"
% KCl In Sylvinita	2.39	35.0	74.5
Bromine (PPM) In KCl	4,340	2,320	2,110
Bromine (PPM) In NaCl	205	110	150
Ratio $\frac{\text{Br in KCl}}{\text{Br in NaCl}}$	21.2	21.1	14.1

Figure 7. Ratios of bromine in KCl/bromine in NaCl in salt core from Dow #8 Salt.

from cooler, more concentrated bottom brines. The observed ratios not only point to separate origins but they also suggest that temperature was a major control in the precipitation of KCl. Alternatively, Valyashko (in Holser, Wardlaw and Watson, 1968, p. 74) comments that, "... NaCl, depending on the temperature, can precipitate in the form of ordinary salt (NaCl) or, at a low temperature (below 0.15°C), in the form of hydrohalite $\text{NaCl} \cdot 2\text{H}_2\text{O}$. In the distribution of bromine between the solution and the

crystals, hydrohalite, with the same conditions, absorbs more bromine than halite, but in the transformation of hydrohalite into halite, i.e., in melting in its water of crystallization, the main mass of bromine passes into the liquid phase, whereas there remains very little bromine in the halite which is formed in this way."

Minor constituents. The sylvinita sections are exceptionally clean. Several analyses were made for minor constituents (Fig. 8). Since the anhydrite is relatively low throughout the salt section and magnesium salts are non-

Depth		%K	%Na	%Cl	SO_4 , ppm	Mg, ppm	Rb, ppm
Meters	Feet						
(2510.6)	8,237	0.2	39.3	59.9	2900	470	<5
(2556.3)	8,387	1.9	40.0	59.5	5600	190	<5
(2528.9)	8,297 ¹	23.7	20.9	53.5	1700	57	32
(2541.1)	8,337	39.2	10.7	50.4	900	71	54
(2555.7)	8,385	41.7	8.4	49.8	2600	21	57

¹Also 7.8 ppm B and 0.13 ppm Li

Figure 8. Minor constituents in salt core from Dow #8 Salt (Anderson and Egleson, 1970).

existent, we are led to speculate that the brine was concentrated to a large extent before it reached the center of the basin, as proposed by Dellwig (1955); and also that diagenesis may have occurred through dolomitization, leaving the bitterns, from which the sylvinite was precipitated, enriched in calcium and depleted of magnesium and sulfate. The deposit belongs in the class of highly $MgSO_4$ -deficient deposits cited by Braitsch (1971, p. 268).

A-1 Salt unit

The A-1 Salt contains the potash. This oldest salt of the Salina Group underlies most of the Lower Peninsula, and has a cored thickness of 449 feet at Midland (Fig. 9).

The rapid thinning of salt in the northwest and parts of the southwest appears to be evidence of truncation by sub-aqueous re-solution before the A-1 Carbonate was deposited. Otherwise, the salt shows a gradual thinning and a well defined anhydrite facies beyond the salt, indicative of a normal depositional zero line.

A-1 potash facies

Bromine in salt cuttings. The salt cuttings from a number of wells penetrating the A-1 Salt were analyzed for

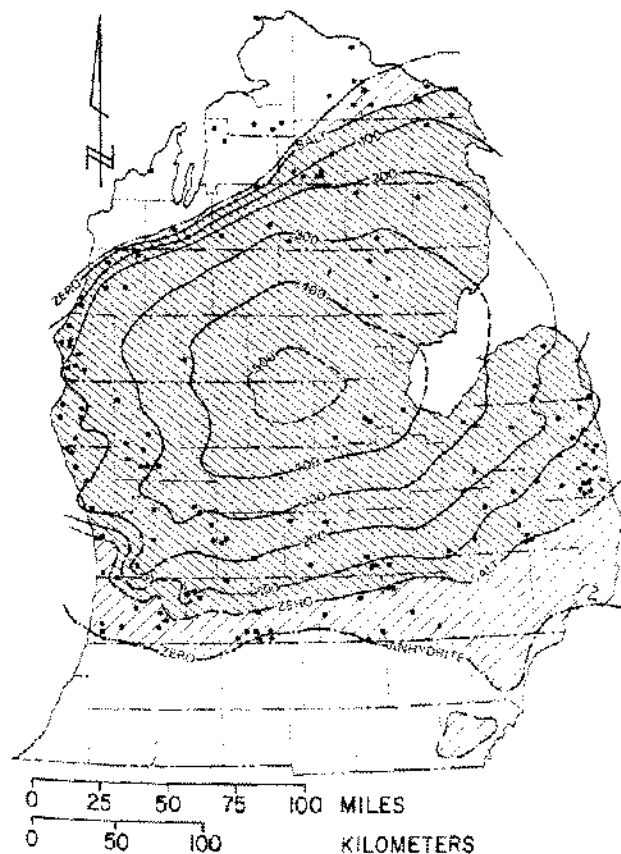


Figure 9. A-1 Salt thickness (After Matthews 1970a). The numerous control points in the southern counties were not posted. Anhydrite zero line in southeast after Briggs, et al., (1964).

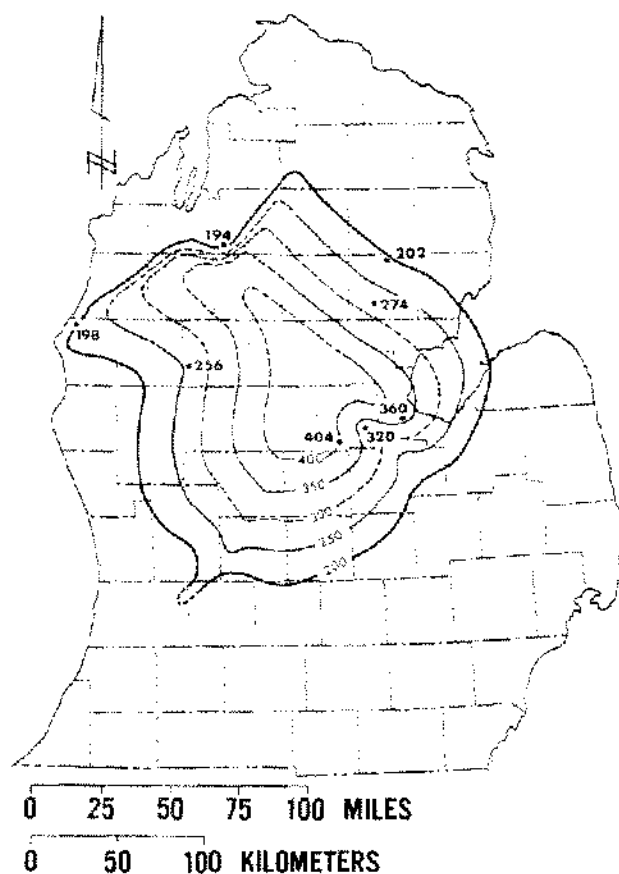


Figure 10. Bromine in A-1 Salt reported in ppm as the average of the five highest analyses.

bromine. The results indicated a widespread deposit (Fig. 10). The vertical placement of the bromine within the A-1 Salt showed good correlation with the core data (Fig. 11). The upper part of the bromine profile, showing a gradual decrease of bromine, is of particular interest as evidence of the slow development of a dilution phase in the first megacycle. The dilution phase is present in bromine profiles from four wells¹ widely spaced across the A-1 Salt basin; from Midland, the well in Mason County is 114 miles (182 km) west-northwest, another in Kalkaska County is 86 miles (138 km) northwest and the Reinhardt well is 44 miles (70 km) north.

Gamma-ray and other logs. Several hundred gamma-ray and other logs of wells have been studied. The "type-log" was the Pure Oil Company #1 Emery (Fig. 12). It is shown here correlated with the Dow #8 Salt core data.

The additional deep-basin wells which have logged the A-1 Salt within the confines of the A-1 Potash in recent

¹Dow #8 Salt (21-14N-2E) Midland Co.; Miller Bros #1 Mikula (3-20N-17E) Mason Co.; Simpson #1 State-Springfield (10-25N-8W) Kalkaska Co.; Ohio Oil #1 Reinhardt (35-22N-2E) Ogemaw Co.

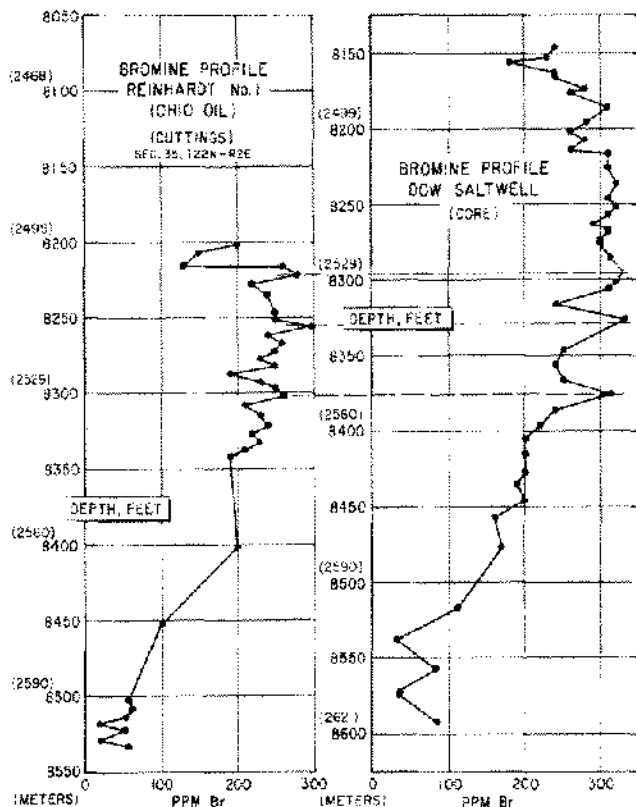


Figure 11. Bromine profiles of two wells 44 miles (70 km) apart (Anderson and Egleson, 1970).

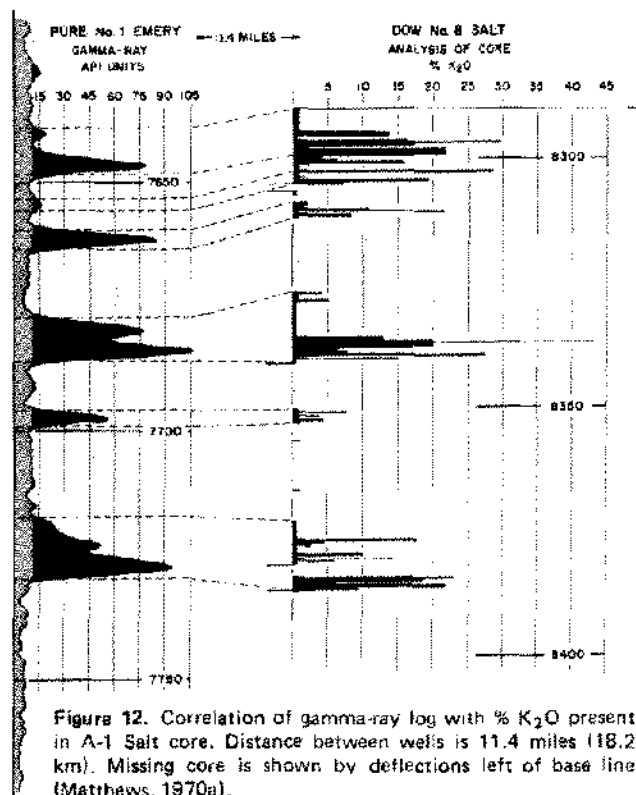


Figure 12. Correlation of gamma-ray log with % K_2O present in A-1 Salt core. Distance between wells is 11.4 miles (18.2 km). Missing core is shown by deflections left of base line (Matthews, 1970a).

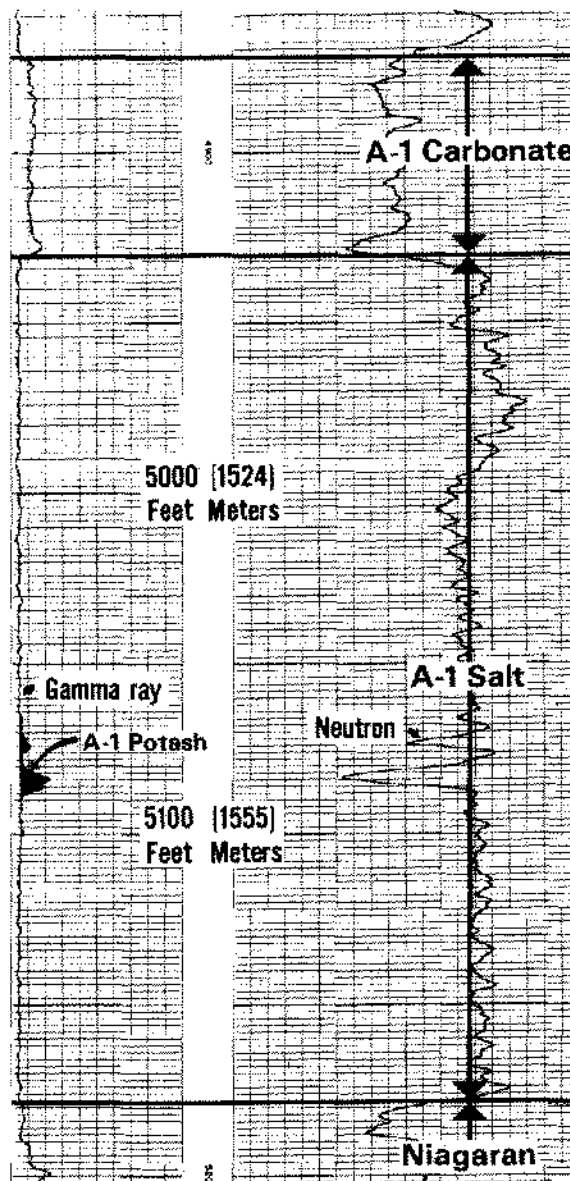


Figure 13. Partial log of Thunder Hollow Oil and Gas #1 Thompson, Sec 20, T15N-R14W, Newaygo County.

years generally confirm the original conclusion that the deposit covers 13,000 square miles (33,800 km^2) of the basin. Figures 13, 14, 15, 16, 17, 18, and 20 illustrate the position and response of the A-1 Potash in typical logs across the basin. The well locations are shown on the facies map (Fig. 21).

A recent well drilled by Dow at Midland was logged, but not cored, and the log shows a considerable increase basin-ward from the "type-log" in the Pure #1 Emery (Figs. 12 & 14).

Clastics in salt. The A-1 Salt had long been known to show radioactive log responses in mid-basin, but these had

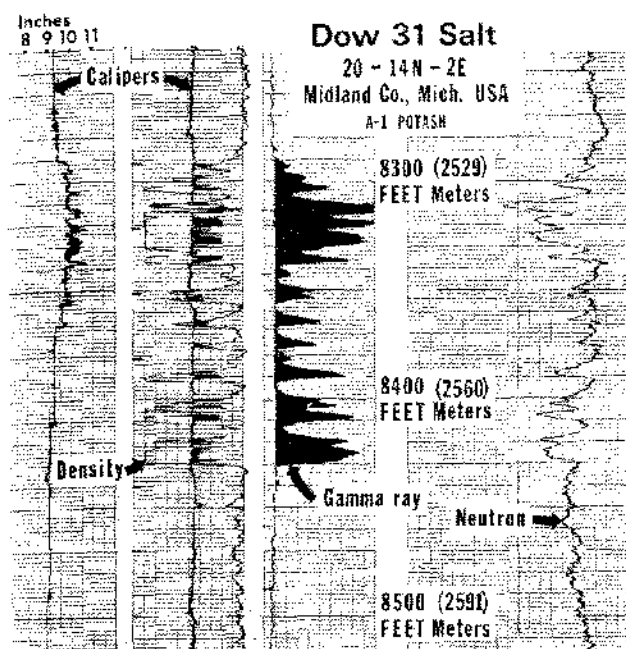


Figure 14. Partial log of Dow #31 Salt, Sec 20, T14N-R2E, Midland County.

always been described as "shale or carbonate lenses" and as such ignored. Similar responses seen in other salts, the upper B, the D and numerous "kicks" in the F salts, are not potash.

The D Salt "kick" had been cored and is composed of clastics² and evaporites; dolomite, anhydrite, salt, illite

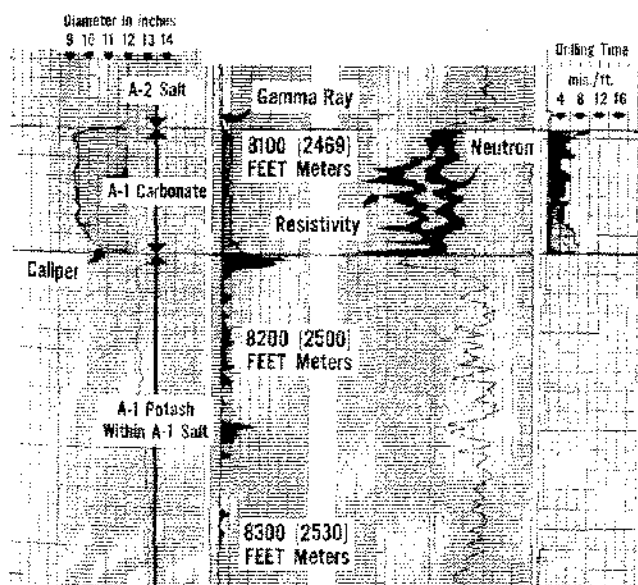


Figure 15. Partial log of Brazos-Sun-Superior #1, State Foster, Sec 28, T24N-R2E, Ogema County.

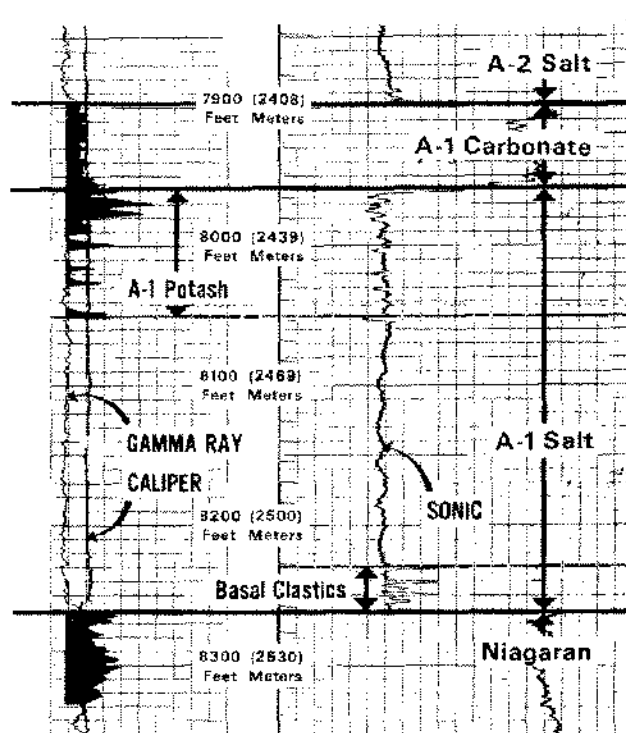


Figure 16. Partial log of Shell Oil Company #1-12, Sec 12, T25N-R2E, Oscoda County.

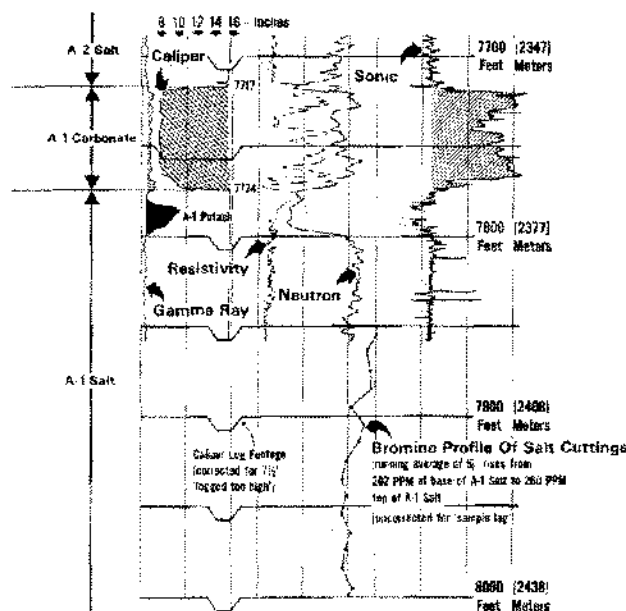


Figure 17. Partial log of Union Oil Company #C-4 State Beaver Creek, Sec 21, T26N-R4W, Crawford County.

²The detrital or non-detrital nature of the "non-saline mineral impurities" has not been proven. Braitsch notes that quartz can be either authigenic or detrital, and illite clay is "generally detrital, occasionally authigenic" (1971, p. 25).

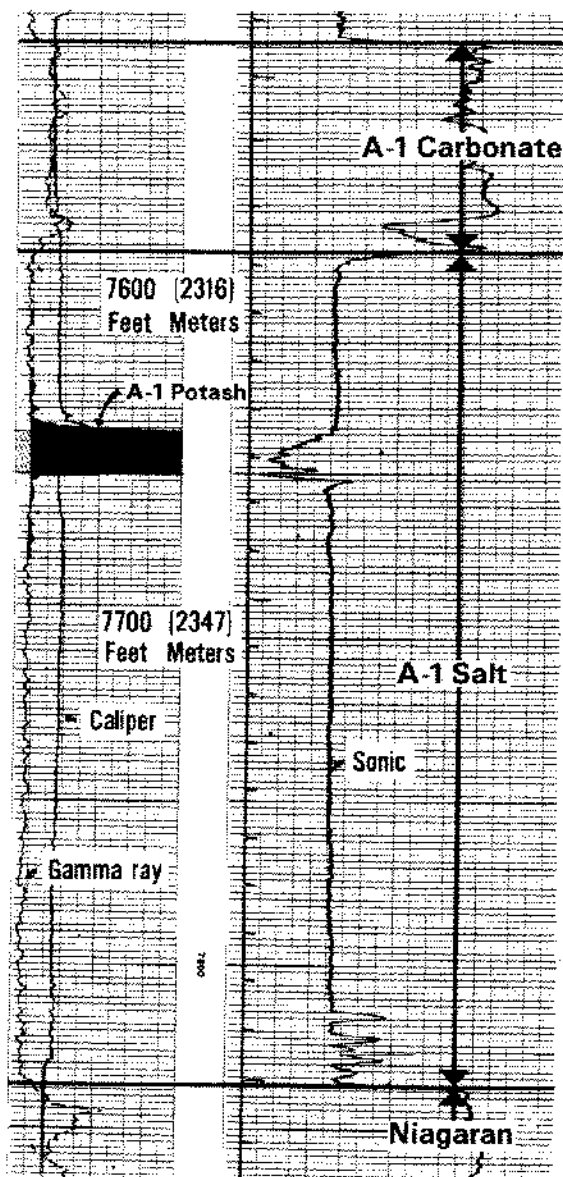


Figure 18. Partial log of Shell Oil Company #1-16 Consumers Power, Sec 16, T26N-R5W, Kalkaska County.

clay and crystalline quartz. These materials are believed to be, in part, windblown and water-deposited; a mixture of allochthonous and autochthonous types which mark the mid-point of a single D evaporite megacycle. The bromine content of cored salt intermingled with these windblown clastics shows higher bromine than the D Salt either above or below. A bromine profile of the D Salt from a core near Sarnia, Ontario (Fig. 19), supports the contention that the D Salt was the result of one large evaporite megacycle which reached a maximum brine concentration as the allochthonous clastics were being deposited.

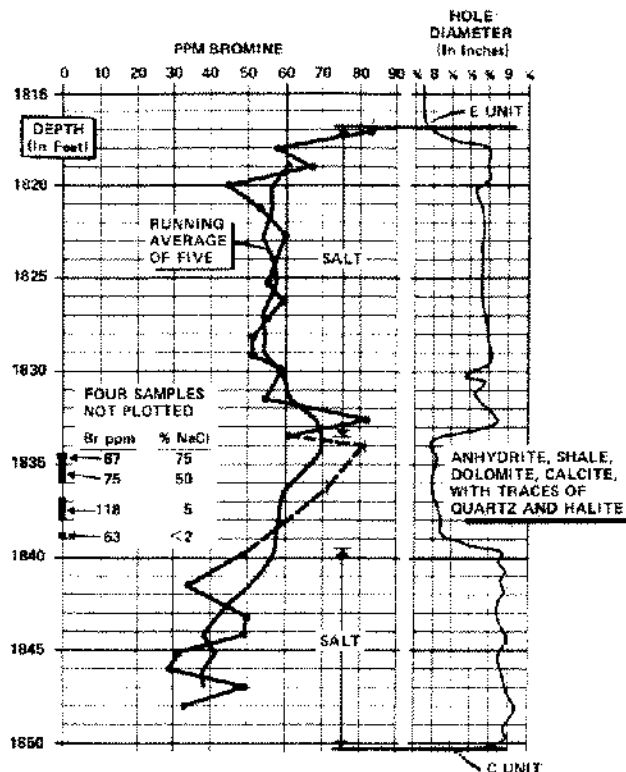


Figure 19. Bromine profile of the D Salt from Dow #43 Dow Farm, Con XII, Lot 24, Moore Township, Lambton County, Ontario, Canada.

Potassium in drilling mud. In one area where the cause of log responses was questioned, potassium was detected in drilling mud near the predicted zero line of the potash deposit (Anderson and Majeske, 1970). Confirmation in the form of a gamma-ray log came later (Fig. 20).

Sections and maps. The probable extent of the potash in the A-1 Salt is shown (Fig. 21) related to the present limits of salt and anhydrite.

Potash should continue to thicken toward the depositional center of the A-1 Salt basin. In the northwest and southwest, where truncation influenced present limits, potash occurs very close to the salt zero line. In other places, the potash zero line marks the depositional limit of the most soluble mineral in a classical lateral lithofacies succession for evaporite deposition from bittern salts to halite to sulfates to carbonates.

In the stratigraphic cross sections the base of the A-1 Carbonate was used as a datum and the total potash-containing interval was outlined.

The West-East stratigraphic cross-section (Fig. 22) shows the very soluble potash lithofacies to be a lense within a lense of halite, and that the lowest potash begins at a position near the vertical middle of the salt deposit. A thin anhydrite surrounding the halite lense is not shown due to problems of scale.

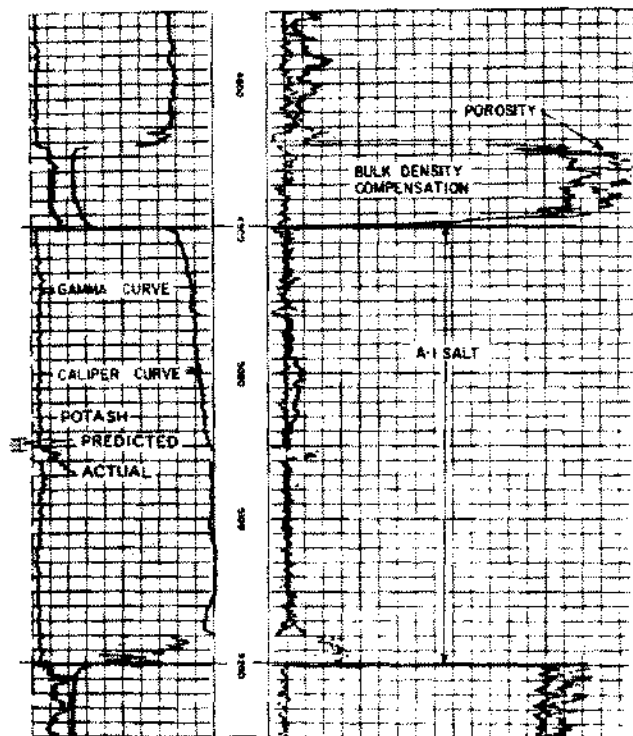


Figure 20. Partial log of An-Son #1 Parmeter, Sec 26, T9N-R10W, Kent County, showing predicted and actual potash within the A-1 Salt (Anderson and Majeske, 1970).

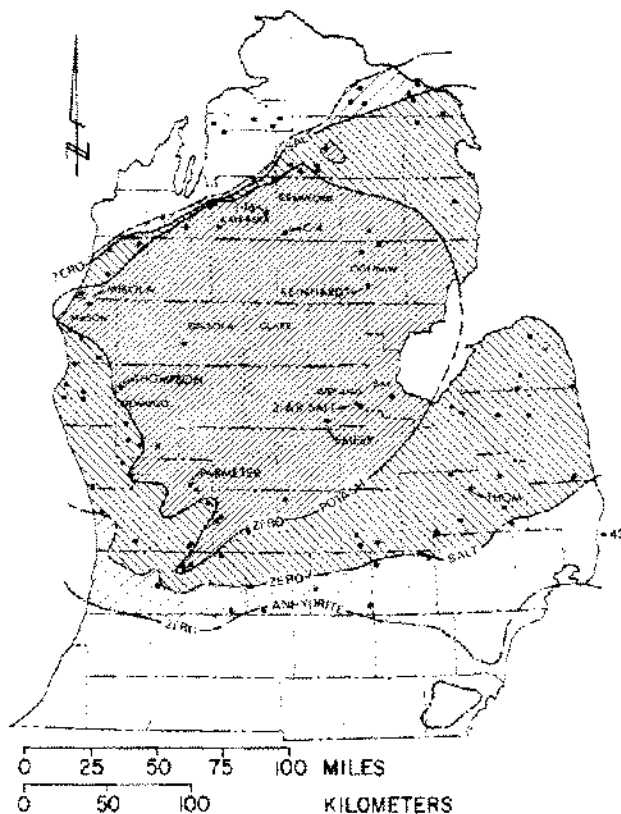


Figure 21. Position of A-1 Evaporite facies and location of key wells (After Matthews 1970a).

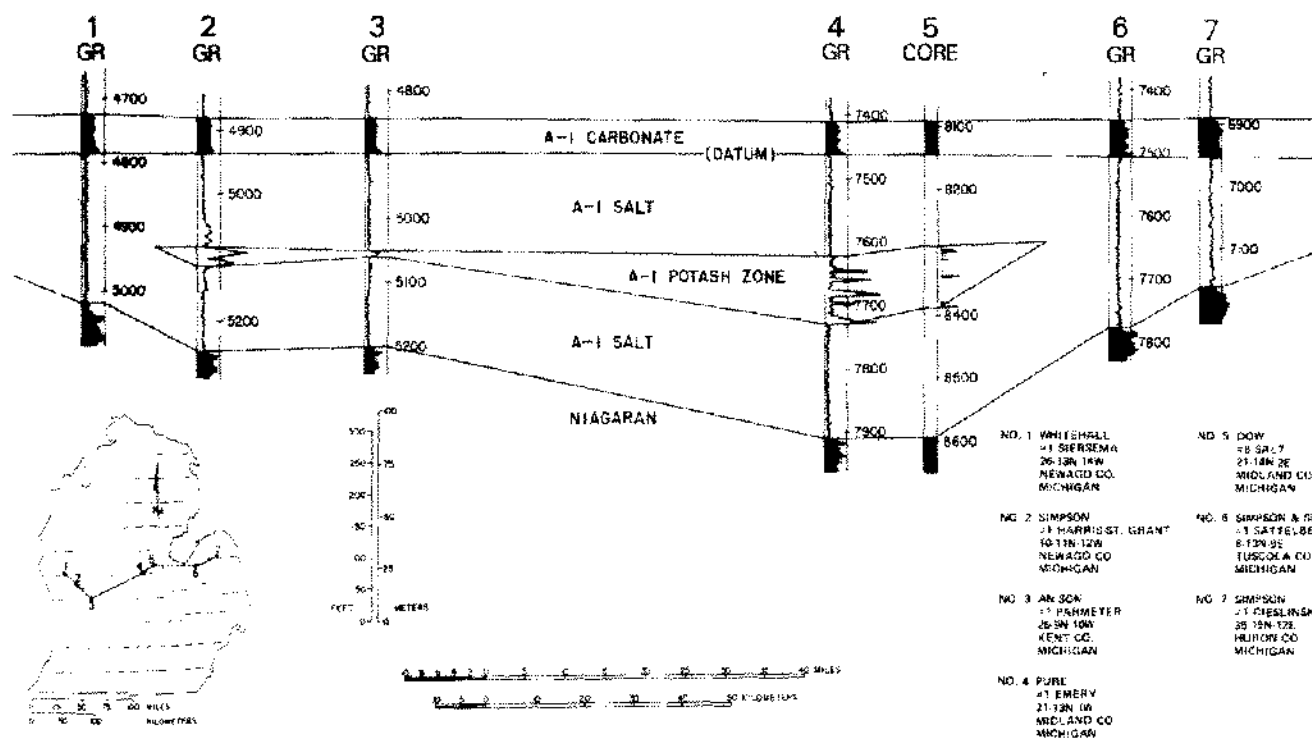


Figure 22. West-East stratigraphic cross-section of the A-1 Salt and A-1 Potash in the Michigan Basin (Anderson, et al., 1972).

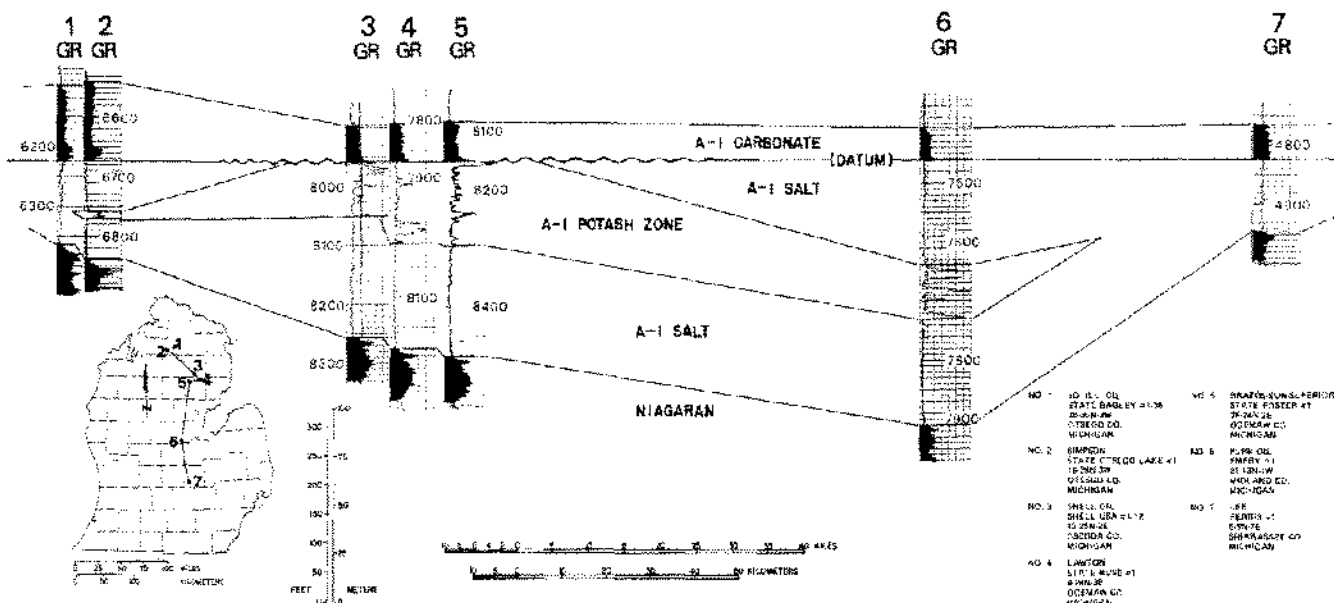


Figure 23. North-South stratigraphic cross-section of the A-1 Salt and A-1 Potash in the Michigan Basin.

The N-S stratigraphic cross-section (Fig. 23), shows an apparent different position of the lenticular sylvite lithofacies with the A-1 Salt. In the north the deposit is found near the top of the preserved deposit, and we conclude that recessive salt above the potash was lost by sub-aqueous re-solution before or during the deposition of the first few feet of A-1 Carbonate. The gamma ray pattern of the A-1 Carbonate characteristically shows a high response at the base; this so called "foot" is more evident in the northeast where presumably the initial A-1 Carbonate deposition occurred in bottom waters enriched locally in potassium ion.

The salt beneath the potash is more uniform in thickness than the salt overlying the potash (Fig. 24). An isopach map of the salt beneath the A-1 potash zone, based on a limited number of control points penetrating the potash, shows a rather consistent and gradual thickening toward basin center, although the thickening is more rapid along the northwest edge of the basin reflecting the change in slope of the sea floor to the north. A map of the zone believed to contain potash (Fig. 25) shows a deposit which thickens basin-ward. An area of unknown size in the northeast has undergone a truncation. The isopach of the salt over the potash (Fig. 26) is considerably different than the other two; a much larger area appears to have been thinned by truncation. The recessive salt deposited over the potash, and preserved in mid-basin, is not now present over the northern potash.

EVAPORITE DEPOSITION

Basic premises

Before discussing the origins of an evaporite lithofacies deposit having the physical geometry and chemical char-

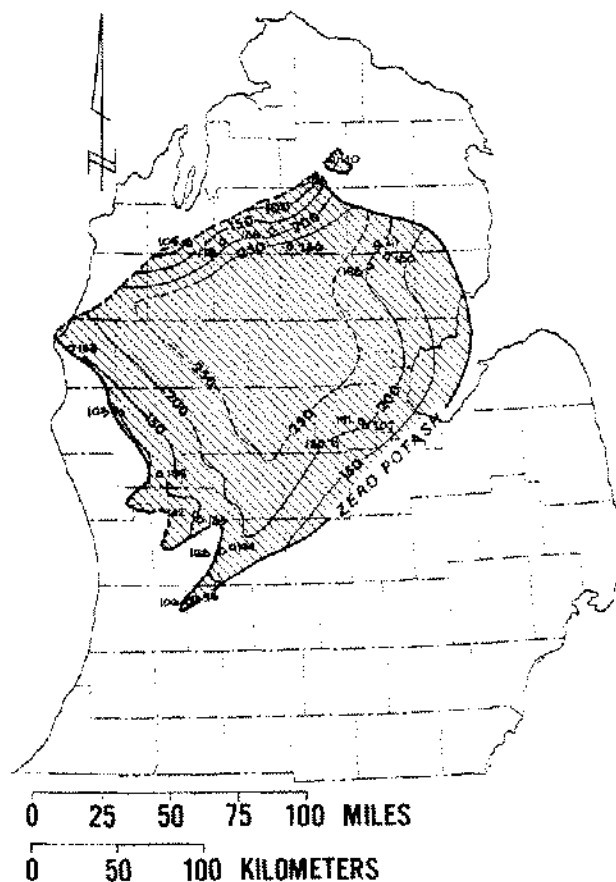


Figure 24. Isopach map of that part of the A-1 Salt below the potash zone.

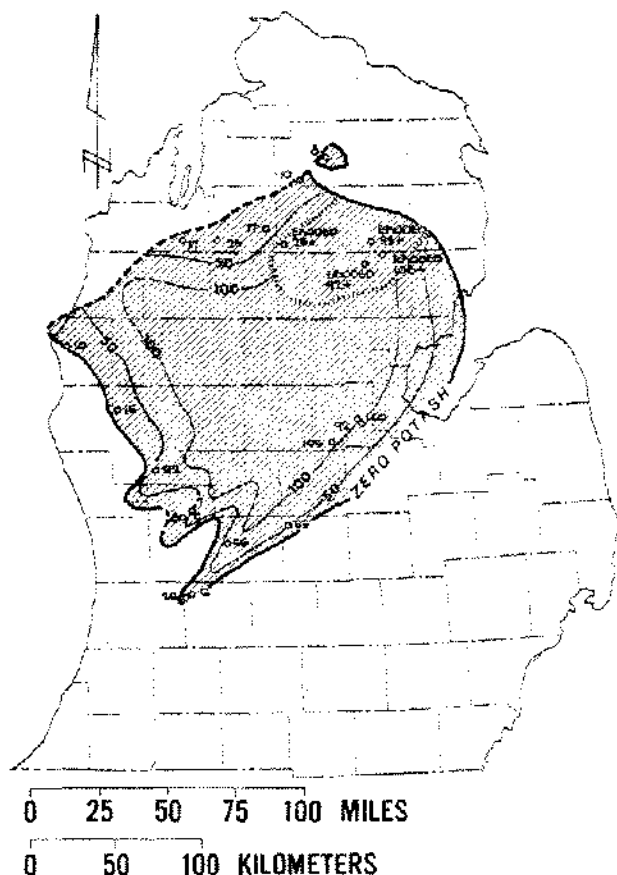


Figure 25. Isopach map of the total zone within the A-1 Salt believed to contain the potash beds.

acteristics described, a review of some of the factors concerning evaporite deposition is in order. Several points will be considered: First, the nature of the evaporite cycle; second, our concept of a "transgressing-regressing body of brine"; third, "stand-stills" in a cycle when reflux is present; fourth, the certainty of potash if reflux is not present; fifth, the influence of radial or convergent influx on flow patterns and facies; sixth, the effect of temperature.

The evaporite cycle. Evaporite deposition is cyclic (Fig. 27). The early stages of a cycle are dominated by factors which cause increasing water concentration, the dessication of Stewart (1963). The final stages are dominated by factors which cause increasing dilution, the flooding of Stewart. The peak of a cycle is reached when the water concentration is at its maximum. Should a cycle proceed to complete dessication, that cycle is interrupted at a mid-point and is not yet at the end of the cycle. The most soluble mineral in an evaporite cycle has to be deposited in mid-cycle and as a result, potash should be expected in the middle of salt sequences, except where the deposits of the upper half of the cycle have been re-dissolved totally or in part. Likewise, the highest bromine in primary halite will be deposited at mid-cycle.

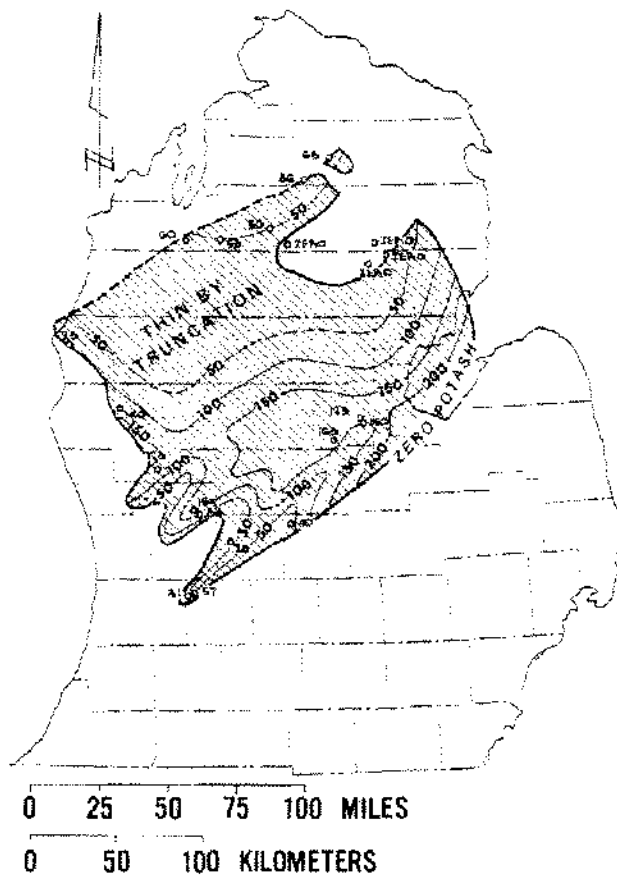


Figure 26. Isopach map of that part of the A-1 Salt over the potash zone.

A transgressing/regressing body of brine. Second, minerals deposited during the early stages of an evaporite cycle are the result of a "transgressing body of brine" (Matthews, 1970a) in which increasing concentration gradients transgress the ocean floor, and in this sense the resulting deposits are transgressive. These are the progressive evaporites of Borchert. These minerals are usually well preserved as they are covered by increasingly concentrated brine, a brine that is transgressing the basin floor.

The deposits of the latter stages of an evaporite cycle are the result of a "regressing body of brine" (Matthews, 1970a). Such regressive deposits, the retrograde or recessive of Borchert, are often poorly preserved as they tend to be covered by brines capable of re-dissolving the bottom sediments. During the dilution phase, strong brines over any given point of the sea floor tend to be replaced by weaker and weaker brines as the concentration gradients regress. Where regressive beds survive without clastic armor, it probably is the result of a thin blanket of insoluble, or less soluble, residues which can hold a protective layer of saturated, interstitial brine on bottom.

As used here, the terms "transgressive body of brine" and "regressive body of brine" apply to the sea floor and to the migration of concentration gradients; the terms do

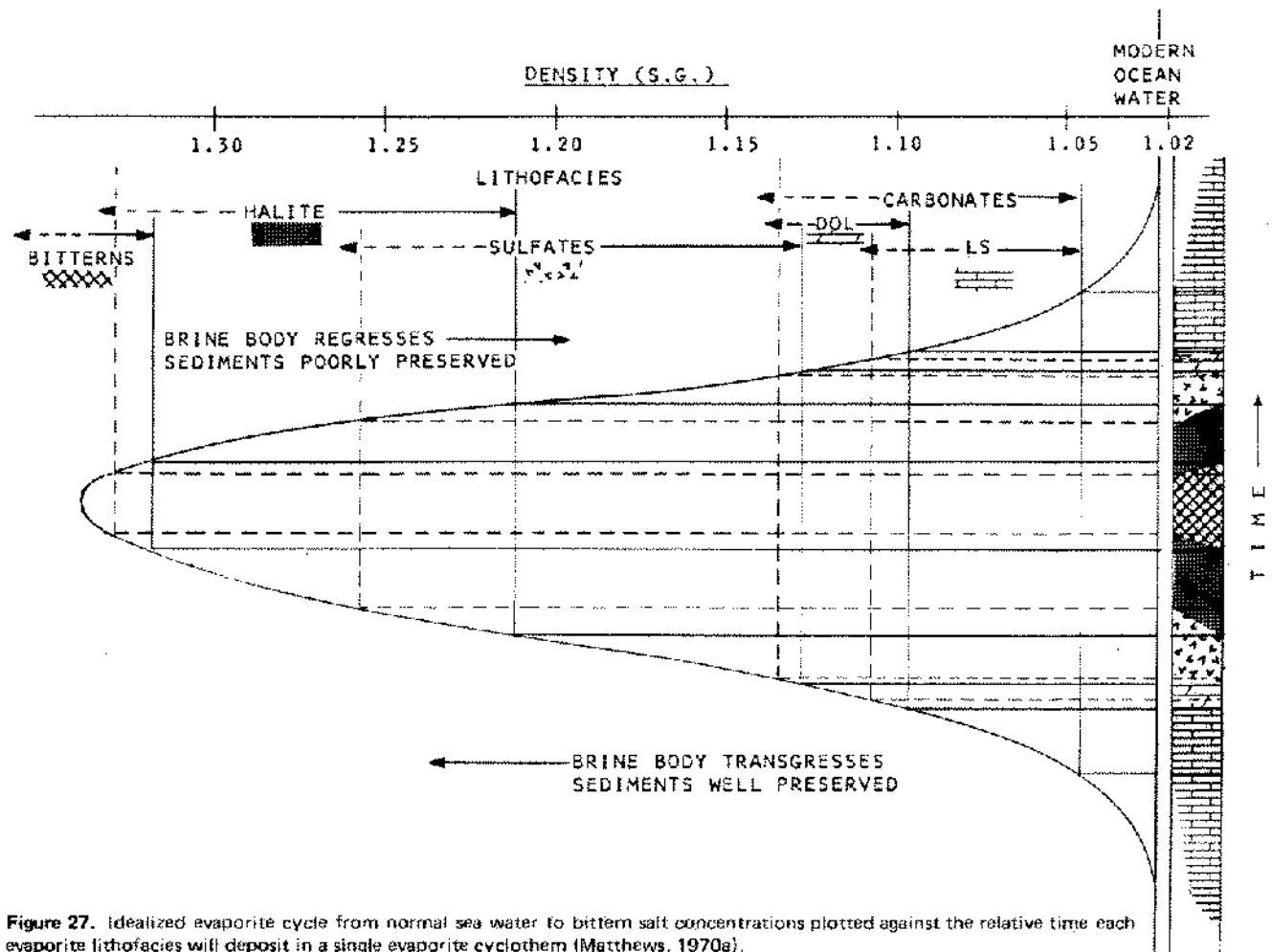


Figure 27. Idealized evaporite cycle from normal sea water to bittern salt concentrations plotted against the relative time each evaporite lithofacies will deposit in a single evaporite cyclothem (Matthews, 1970a).

not imply changes in shore lines. The terms are not synonymous with "transgressing sea" or "regressing sea." Shore lines need not change as the influence of the brine body changes across the bottom of the basin, however, the increasing influence of a transgressing brine body will occur normally during the concentration phase of an evaporite cycle. At that time, sea levels may be dropping and shore lines may be regressing. It is important to consider our contention that the events occurring on any given position on the sea floor of an evaporite basin are independent of distance to actual shoreline or to the depth of water. A change from one evaporite lithofacies to another does not mark a shoreline, but only marks the transgressive limit in the migration of a concentration gradient in the brine on bottom.³

Dynamic equilibrium. Third, reversals or dynamic equilibrium conditions can occur at any point in an evaporite cycle, but only if reflux to the open ocean is present. In a restricted basin having no reflux, a complex mixture of ions continues to enter while water leaves by evaporation. Certain ions are removed by precipitation, while the

³The established usage of the terms "transgression" and "regression" as applied to sea levels is poorly adapted to a succession of autochthonous evaporite minerals. Following conventional practice, Hite (1970, p. 61) described as regressive a sequence of evaporite minerals accompanying a lowering of sea level, but the evaporite facies he described display the results of an actively "transgressing body of brine"; in ascending order, anhydrite, halite, potash. The important factors as seen preserved in the evaporite rock record concerned the composition and concentration of the parent brine, as well as the geometry and migration of the concentration gradients within the brine as these factors relate to a point on bottom, not the movement of a distant shoreline.

We believe the concept of a "transgressing-regressing body of brine" to be valid and helpful in understanding evaporite rocks, however, the attempt to explain the concept with terms so firmly linked to the movement of shorelines has been criticized. Other terms, such as "prograde" and "retrograde" can also be confused with shoreline movement and/or metamorphic change. The modern use of "progressive" and "regressive" generally implies metamorphism, although "progressive overlap" as used by Grabau in 1906 to describe "a spreading of the 'zones of deposition'" (Gloss. of Geol., AGI, 1972, p. 369) fits the concept very nicely. A "zone of deposition" as defined by a given concentration gradient can spread, expand, transgress, prograde, advance, or migrate over a specific site on the sea floor. If the concentration gradient enclosing the spreading body of brine separates brines capable of depositing halite from brines less concentrated, then the transgression of that brine body will be evidenced by halite over sulfate. Thus, the halite will show a "progressive

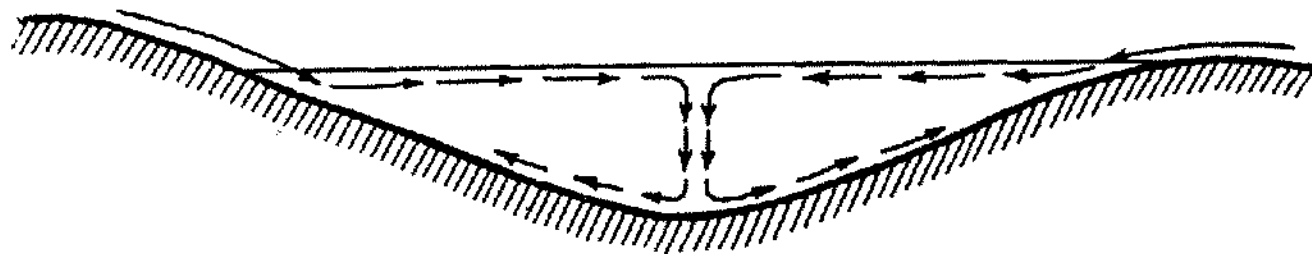


Figure 28. Ideales Strömungsbild in einem gleichförmig gestalteten Salzsee bei gleichmäßigem Zustrom und Windstille. (Ideal circulation pattern in a symmetrical salt lake with radial inflow uninfluenced by wind). From Lotze: "Steinsalz und Kalisalze," Gebrüder Borntraeger, Berlin/Stuttgart, 1957, page 96, Abb. 48.

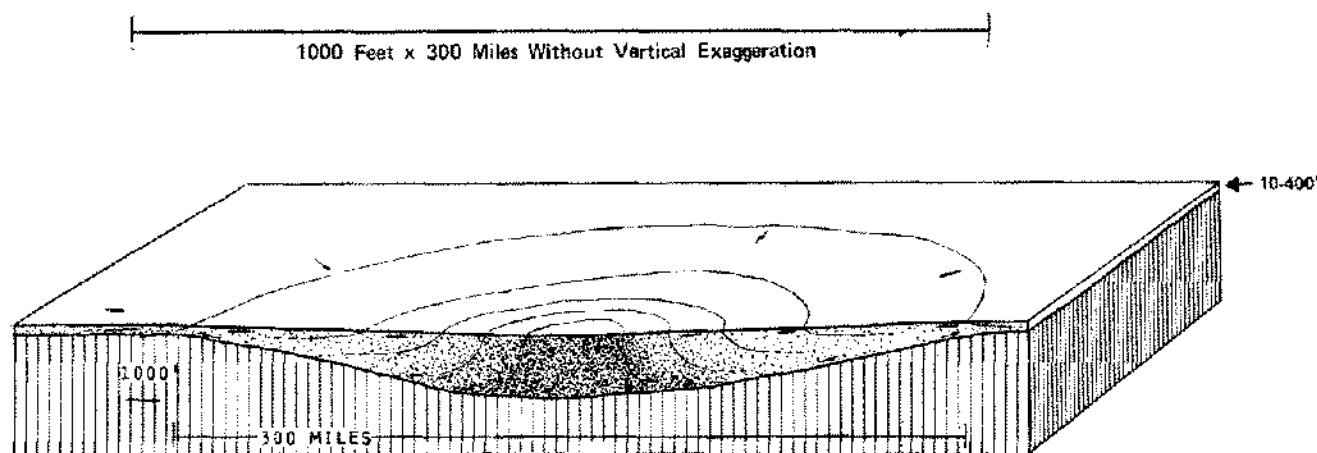


Figure 29. Circulation in a basin restricted by shallow water margins and having convergent inflow and radial reflux. The most concentrated surface brines are near mid-basin (After Matthews, 1970a).

remaining ions continue to accumulate in solution. The arrest or stabilization of a cycle in dynamic equilibrium would be impossible without reflux (King, 1947; Scruton, 1953; Hite, 1970).

Absence of reflux. Fourth, if no reflux of bittern brines out of the basin is permitted, and the other factors favoring increasing sea water concentration do not change, the cycle must move to the eventual deposition of potash salts regardless of depth. Borchert and Muir (1964) have said, "We believe that a wide range of depth is still possible even in the last stages of precipitation when the potash salts have started to separate out. There is absolutely no need for this phase to be associated with very shallow basins or with complete dessication" (p. 43). Hite (1970) has stated that "without reflux the evaporite deposits of all basins would include the full spectrum of evaporite minerals . . ." (p. 50).

Radial or convergent inflow. Fifth, the number and distribution of inlets exerts a strong influence on the pattern of evaporite facies distribution within the basin. In a one inlet model, the densest surface water will be found along

shore, away from the inlet or open ocean (Briggs, 1957; Scruton, 1953). But Briggs and Pollack (1967) showed that radial or convergent inflow was more realistic for Michigan. Now with convergent inflow, the densest surface water will be near center (Lotze, 1957) (Fig. 28). Surface water will then slope down to a low area of minimum surface movement in a central position of the basin (Fig. 29). This surface low will contain water which is as concentrated as any in the basin (Matthews, 1970a). These centrally located brines will sink under the surface low. Bottom currents of this brine will move from under the surface low into any accessible lows in the basin floor.

Survival of the evaporite minerals deposited in a basin receiving radial inflow will occur first in the deep central part of the basin under the surface low. The densest brine in the system will sink and transgress the basin floor from

onlap" over the sulfate, and this geometry will be unrelated to any local shoreline. The "onlap" will have occurred some unknown distance from shore and in an undetermined depth of water. We are dealing with a "submarine transgression."

the center outward toward the rims. In the center of the basin the heaviest brines will be continuous from the surface low to bottom, and in this way, the dense bottom brine will remain in contact with the solar evaporation process even in deep water.

As the evaporite cycle continues in the direction of increasing concentration, this brine body will transgress across the basin floor and the central column of sinking brine will increase in diameter. The densest brine will always be found under the surface low in the core of the sinking column. Bromine values in any halite bed deposited in such a manner will decrease toward the edge of the basin; such a decrease has been observed (Holser, 1966; Kunasz, 1970).

The lightest marine brines in an evaporite basin are always those entering. Being less dense than the brines already in the basin, the influxing brine will float in on top of the existing brine surface and move toward the area of greatest surface water concentration. The new influxing water will not slide down the slope of the sea floor as a bottom current.

If the influx is not totally radial or convergent then some parts of the basin margins may develop characteristics of a "distal shore." In that case, the denser brines will shift from an idealized central location toward that "distal shore." Brines will continue to sink under the surface low and, if the surface low shifts toward a "distal shore" because of uneven influx, a bottom current can develop which could transgress from "distal edge" toward basin center as envisioned by the advocates of one inlet model. In that case, bromine values in any given salt bed could decrease away from the "distal edge" toward basin center; such a decrease has been described by Baar (in Schwerdtner and Wardlaw, 1963, p. 245).

Cooling. Sixth, an expected cooling at depth, will contribute to the bottom growth of crystals. Borchert and Muir (1964) have stated that, "cryophilic sylvite would tend to accumulate in the deeper, cooler basins, while only thermophilic halite might develop in shallower, warmer waters" (p. 199). Braitsch (1971) concludes that, "... in large salt seas the greater part of the salts, particularly the chlorides, are precipitated as a consequence of the cooling which occurs as the saturated solution sinks into the basinal solution" (p. 262). Others have cited laminated solar ponds and believe that lower level brines should be warmer (Garrett, 1970; Hite, 1970).

CONCLUSIONS AND IMPLICATIONS

Depositional history in Michigan

Early basin conditions. We believe the thickness and relative purity of the A-1, A-2, and lower B Salts are best explained by the inertia of a large mass of brine found only in a deep basin. The 1967 study led the senior author to

conclude that the Michigan Basin was 600 or more feet deep in mid-basin before the first anhydrite of the Cayugan was deposited, deep enough to receive the A-1 Salt without filling (Matthews, 1970a). We believe this to be still valid. The deep basin origin of these salts has been proposed by several, most recently by Rickard (1969 and 1970).

We picture the early basin as a deepening depression in an otherwise relatively flat sea floor. The bottom slopes in the basin were gentle, in the order of 1:1000.

The New York-Ohio evaporite basin was not yet restricted beyond the point of carbonite deposition, for the oldest evaporite there is not as old as the A-1 Salt (Ulteig, 1963; Fergusson, et al, 1968; Rickard, 1969).⁴

We believe that the water-covered approaches to the Michigan Basin were wide and shallow and the water entering the basin was more saline than open ocean water. The influx of water was essentially convergent and barriers, when they developed, were as much a matter of the dynamics of shallow water margin conditions as they were of physical barriers, such as reefs. The numerous reefs and extensive carbonate banks around the rims had considerable relief and certainly they contributed to the degree of restriction in the early basin. We believe, however, that the inlets were numerous and that the reefs were "leaky," i.e. relatively permeable. The dry land exposed in these scattered reefs and associated island arcs during periods of lowered sea level was of small areal extent. Shorelines were of little consequence to earliest mid-basin evaporite deposition, but they became more important with the passage of time as the source of wedges of waterborne clastics, found near the basin rims, which occur more frequently in the younger salts.

Clastics in salt. We believe the relative absence of clastics in the first few salts is evidence that most of the marginal areas were water-covered through the first three evaporite megacycles. No extensive source areas were exposed to sun and wind for any great length of time.

Water movement was slow within the restricted basin and waterborne clastics tend to appear as local marginal wedges. As the mid-point of the megacycle is likely to coincide with the lowest water stage over the basin margins, a time when the reefs are exposed, these waterborne clastics can be expected to occur most frequently in a mid-position of edge salt, assuming little or no loss of the "recessive" salt (Fig. 30).

Windblown clastics are also to be expected at mid-cycle but their lateral extent is quite different; these clastics will

⁴During a Conference on Silurian Stratigraphy held April 23-24, 1973 at the University of Michigan, Ann Arbor, Michigan, Arie Janssens of the Ohio Geological Survey suggested that anhydrites in Ohio, formerly assigned to the B Unit, may be correlative with the A-1 Evaporite and A-2 Evaporite in the Michigan Basin.

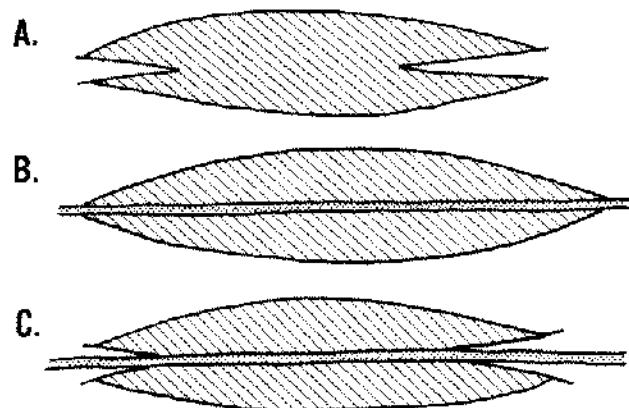


Figure 30. Clastics in halite lenses. A. Water-borne. Basin margin partially exposed at mid-cycle. Reef tops erode; B. Wind-blown. Basin margin widely exposed at mid-cycle. Epairic sea bottoms exposed to subaerial erosion; C. Wind blown sheet is always associated with water-borne wedges (Matthews, 1970a).

tend to form thin sheets covering large areas. Windblown clastics will mark periods of exposure of extensive mud flats and recent ocean bottoms outside of the basin proper. They will represent "time lines." Numerous authors have considered wind transport for various types of clastic deposits in salt (Borchert and Muir, 1964; Delwig, 1955; Adams, 1969). As sea level lowers enough to expose source areas for windblown material both types of clastics will occur together.

Regardless of how the allochthonous clastics were transported, we believe their absence is evidence that no large local source for clastics was available.

Potash in salt. If a deep water megacycle reverses slowly enough, most of the recessive salt above the potash will be preserved, there will be no break in sedimentation within the salt, and if the rims remain water-covered, no clastics will be present (Fig. 31). If the potash is the result

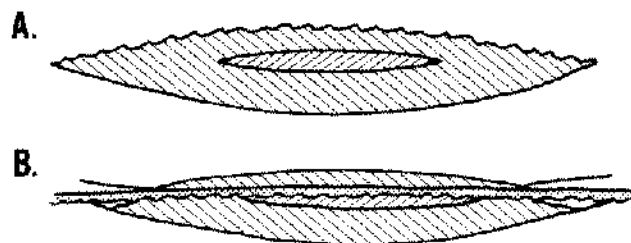


Figure 31. Potash in halite lenses. A. Deep basin potash. Basin margins water covered throughout the cycle. Some sub-aqueous resolution of "recessive" salt; B. Shallow water potash armored by wind-blown and other clastics and covered by redeposited salt. Margins and most of basin exposed at mid-cycle (Matthews, 1970a).

of a shrinking sea or evaporation to dryness, there remains the problem of preserving the highly soluble deposits during the last half of the cycle yet to come. The most common preservative is a clastic armor, generally windblown, accompanied by waterborne clastics and brine containing re-dissolved halite. The potash will be associated with an erosional unconformity. The placement of the potash in Michigan more closely resembles the ideal deep basin potash (Compare Figs. 22 and 31).

Control by eustatic changes in sea level. The degree of restriction in the deep Michigan Basin was controlled by eustatic changes in sea level (Fig. 32). These changes in sea level were similar to suggestions made by Silver and Todd (1969) for the Permian and by Peterson and Hite (1969) for the Pennsylvanian. Concerning Michigan, similar control has been advocated by Rickard (1969) and most recently by Mesolella (1972).

During mid-basin potash deposition, a very small rise in sea level increased the influx and permitted reflux currents to move out of the basin for the first time. This gradual start of reflux of bittern brines out of the basin caused the evaporite megacycle of the A-1 to reverse very

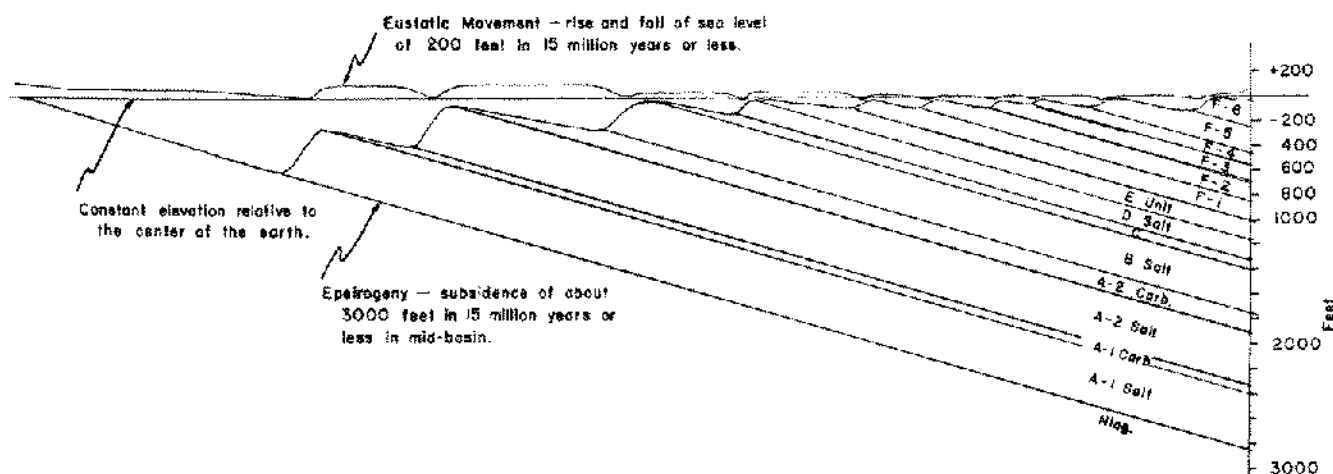


Figure 32. Factors controlling the formation of mid-basin Salina evaporite cyclothems in Michigan (Matthews, 1970a).

slowly and potash deposition was interrupted. It is probable that much of the diluting influx during the latter stages of the A-1 Salt megacycle came from the north or north-east. Re-solution of halite above the potash occurred in northern Michigan and an unknown volume of northern potash was lost during the recessive phase of the megacycle.

The A-1 megacycle ended, while in a halite phase, with a rise in sea level sufficient to end the influence of sea floor shape on surface flow. The dense mass of brine in the basin, concentrated to the point of halite deposition, was trapped. These heavy, stagnant brines were removed from surface evaporation. Halite deposition stopped. Deposition changed from halite to carbonate directly without much sulfate. Oxygen was no longer carried to bottom.

The A-1 Carbonate deposition was slower than the rate of mid-basin subsidence.

The end of A-1 Carbonate deposition was caused by a lowering of sea level to earlier evaporite levels with the basin rims remaining largely water-covered as before. In this way, the trapped body of brine, still concentrated to the point of halite deposition, was again rather suddenly exposed to evaporation. Bottom sediments reverted from carbonate to halite with a minimum of sulfate, which might otherwise be expected if a normal concentration cycle had had to start anew. The A-2 Salt megacycle moved quickly to halite deposition without clastics. Dynamic equilibrium was soon established in the halite range and, because of early reflux, due in part to trapped brines, potash concentrations were never reached. The A-1 deposition had caused a partial filling of the lowest parts of what still remained a deep basin, and this partial filling also contributed to early reflux. With reflux and basinal circulation started, oxygen again reached bottom.

The second inter-cyclic carbonate, the A-2 Carbonate, was the result of high water as was the A-1 Carbonate.

The B-Salt began with trapped brines left over from earlier cycles as did the A-2 Salt.

The trapped brines received some considerable volume of re-dissolved halite added as the basin subsided and sea floor salt around the edge of the deposit was exposed to the lighter surface waters where the salt was subaqueously re-dissolved (Fig. 33). The younger salts, A-2, B, D, and F's show rather low bromines as a result. Eighteen Dow analyses from younger salt in Michigan averaged only 100 ppm and five of the group were 50 ppm or less. The D-Salt from a well in Ontario⁵ (Fig. 19) averaged 55 ppm with 27 samples that ranged from 29 ppm to 83 ppm. Kunasz (1970) reports bromines from edge salts in the F Unit ranging from 35 ppm to 59 ppm.

We conclude that each of the younger cycles contained a substantial portion of re-dissolved, second-generation, bromine-deficient halite. Bromine profiles in the younger salts are not a true measure of the concentration levels of the brine in those megacycles.

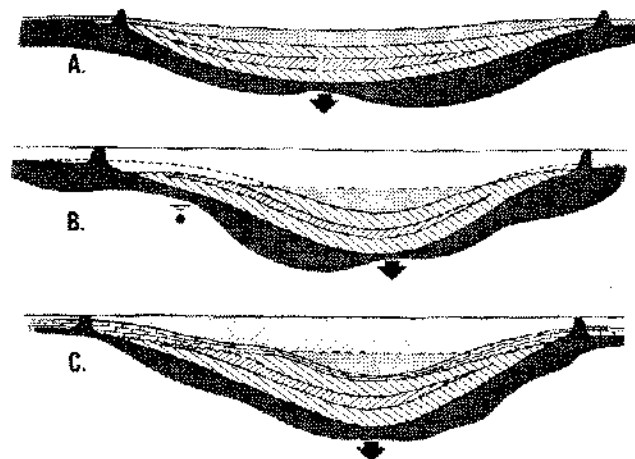


Figure 33. Sub-aqueous re-solution of salt exposed to unsaturated surface layer water. Represents north-south sections through the Michigan Basin. A. Post-A-1 Salt. B. Upper salts in north redissolved as basin subsides. C. A-1 Carbonate deposits.

In support of deep-water evaporites

We have interpreted the data presented here to indicate a deep-water origin for the A-1 Salt, the A-2 Salt, and the clean salt of the lower B Unit in mid-basin. We believe the bathymetric basin to have been its deepest at the close of Niagaran, and that it became progressively shallower with the end of each evaporite megacycle. The basin was intermittently a "filled" basin by the time of late B-Salt deposition (Fig. 34). The salts of the D and F Units, which correlate with the Syracuse formation of New York State, appear to have been deposited in relatively shallow water.

Basin subsidence continued throughout the Cayugan but not until near the end of B-Salt deposition can one picture a shrinking sea with epicontinental sea bottoms exposed to wind and wave as a source of clastic sediments. Thus, the individual evaporite cyclothems and the presence or absence of clastic material, foreign to Shaw's (1964) pure autochthonous evaporite succession, can be used to estimate the fluctuations in water depth over the basin rims.

Unlike a marine beach sand, the depositional edge of an evaporite facies does not define a shoreline, but only marks the extent of a transgressing body of brine acting on bottom. Schmalz (1966) has pointed out that as changing conditions cause gradients to migrate within the basin there will be a corresponding displacement of the facies boundaries and that these changes, "... will be reflected in the evaporite sequence as transgressions or regressions, ..." (p.4). The zones of facies deposition in the A-1 Evaporite indicate, not a shrinking sea, but rather that there was a three dimensional zonation of brine within the basin.

⁵Dow #43 Dow Farm, Con XII, Lot 24, Moore Twp., Lambton Co., Ontario, approximately 3 miles (4.8 km) ENE of Corunna, Ontario, Canada.

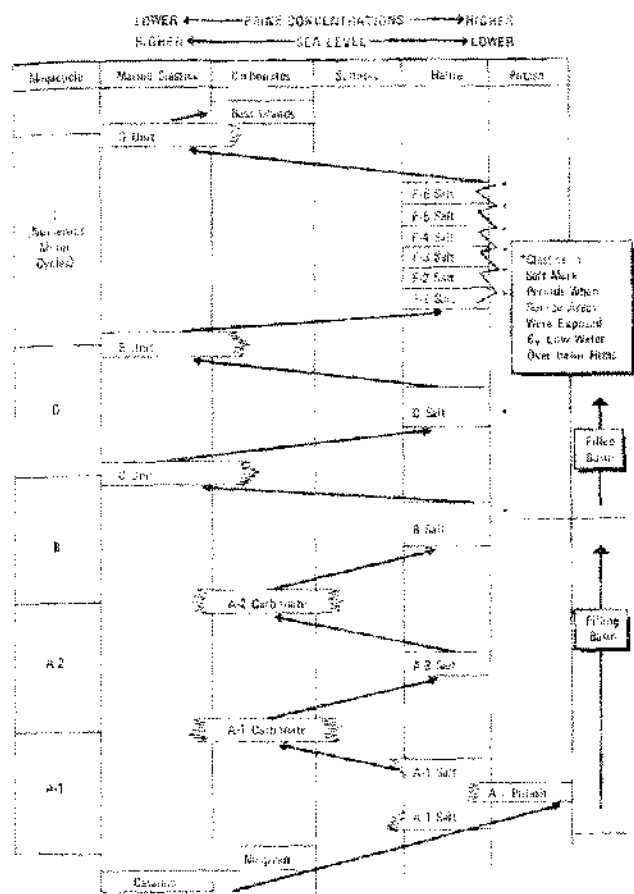


Figure 34. Evaporite succession in the Salina Group of Michigan showing variation in brine concentration as the megacycles developed.

In a discussion of rhythmic bedding, Braltsch (1971) argues that, "... the limit of gypsum or halite saturation in the surface layers at different times of the year must have lain at varying distances from the bar," (p. 253). Such horizontal displacements of the saturation limits for a given solid phase are, in the terminology of this report "transgressions or regressions of the brine body."

W. D. Stuart's (1971) computer study of a wind-driven model for evaporite deposition predicted, "... that saturated brine would be the dominant bottom environment at the present north and east margins of the Michigan Basin," (p. 15) and "The model predicts that hopper crystals should be concentrated around the northeast margin of the basin," (p. 14). In discussing salt preservation in a model where water depths decrease gradually toward the margins and where layered brines of different density are concerned, "... the layered interface will intersect the salt covered sea floor near the margins in a geometry that partially depends on bottom topography. Thus, salt preservation will be topographically controlled, and the eastward displacement of hopper and total halite predicted by the model may be sharply attenuated or removed" (p. 18).

By this analysis, the "favored" upwelling and exposure to evaporation of the deep brine layer in the northeast results in deposits along that margin which may not survive a return to flat-layer, no-wind, "normally," for at that time the evaporites in the northeast would be exposed to unsaturated, upper-layer water. Consider our map of recessive salt over the potash (Fig. 26).

The arguments and inferences which suggest to us deep water in mid-basin, fall into several broad categories: First, the "inertia" or "flywheel effect" of a large mass of brine; second, the co-existence of two brines with the implication that this requires storage space, i.e. depth; third, the lack of any unconformity associated with the time of A-1 Potash deposition; and fourth, other factors related to water depth either in mid-basin or over the basin rims.

Inertia. The aggregate mid-basin thickness of the "clean" salts in the three oldest megacycles exceeds 1000 feet (300 m). The volume of sea water passing through the evaporation process was enormous; for every 100 feet (30 m) of halite 200,000 feet (60,000 m) of normal sea water, under static conditions, must be evaporated (Hite, 1970). Conditions were not static and a continuing influx of sea water was required. Under the controlled conditions of industrial solar ponds, exactly sequenced brines can be formed in shallow water, but "in nature, fairly deep basins must be inferred even with reasonably well sequenced progression of brine," (Charette, 1970, p. 221).

1. The thickness and relative purity of the halite in the lower salts suggests the slow, regular change of a large body of brine.

2. The evaporite megacycles younger than the A-1 Salt; the A-2 Salt, the several cycles of the B, and the numerous cycles of the F, are generally represented by progressively thinner sequences; they appear to have cycled more quickly as the basin filled and as the brine involved in each megacycle became smaller in volume.

3. The general shape of the bromine profiles in the A-1 Salt is evidence of one large basin-wide evaporite megacycle with a single concentration phase followed by a single dilution phase. This pattern, illustrated by the "smoothed" or running average curve (Fig. 35) suggests the slow change of a large body of brine. We don't see how small volumes of water on a tidal flat could result in such a broad general pattern.⁶

The co-existence of two brines. Evaporite deposits derived from two or more brines suggest a basin sufficiently large to provide the storage space necessary to hold and preserve the brines as they evolve.

⁶If the halite of the A-1 Salt in the Michigan Basin center formed by *in situ* replacement of pre-existing sabkha rocks as has been proposed for other center basin salts by Sherman (1970) and by Friedman (1972), then the question must be asked regarding the source of the bromine ion and the explanation of the overall trend of the bromine profile through 450 vertical feet of relatively pure salt. (Fig. 35)

1. Vertical variation of the bromine profiles, a variation which appears not to be random, but to fit a broad range pattern paralleling the "smoothed" curve, suggests to us that the salt precipitated from two sources, i.e. a surface brine of one concentrated and a second more concentrated bottom brine.

2. The ratio of bromine in sylvite to bromine in halite is 20 or 15 to 1 in the A-1 Salt at Midland (Fig. 7). Braitsch states that 10 to 1 is normal. We believe some of the halite came from a different brine, i.e. surface water, and the sylvite came from a deeper brine.

3. The Michigan sylvite may have been formed by the mixing of two brines as proposed by Raup (1970) who reports that, "Experiments using artificial and seawater brines indicate that halite and sylvite can be precipitated by mixing brines of differing stages of evaporation . . . and "Sylvite could be precipitated as a primary mineral," (p. 2246).

No unconformity when A-1 Potash was deposited. If the mid-basin potash deposition were associated with a "shrinking sea" or the local product of the shallow waters of tidal flats, salt pans or sabkhas, there should be ample evidence of erosional unconformity at the stratigraphic position of the potash. Adams (1970) points to the discontinuities and clastic-bearing intervals within the evaporite stratigraphy of the Salado Formation, as evidence of the shallow water environment of potassium deposition in the Carlsbad District. Lacking such evidence within the A-1 Salt, shallow water in mid-basin is denied and deep water is inferred.

1. No clastics are found in, over, or immediately lateral to the stratigraphic position of the potash.

2. No second-generation, redeposited, bromine-deficient salt is associated with, over, or immediately lateral to the stratigraphic position of the potash.

3. Bromine profiles of the A-1 Salt show gentle reversals above the potash in the recessive salt during the dilution phase, not abrupt changes (Fig. 35).

Mid-basin factors. There appears to us to be a worldwide relationship between thick evaporite deposits and those basins showing the greatest rate of subsidence; also between the position of evaporites in the geologic column and the period of greatest subsidence in any given basin; also perhaps, between the most soluble evaporites and the period of fastest subsidence in any given basin.

1. The thin Niagaran rocks of mid-basin suggest to us deep water in a "starved" basin.

2. The five or six thin, black, calcareous shales having a sulfurous odor present in mid-basin in the basal A-1 Salt are believed to be rocks laid down under the euxinic conditions expected in a deep basin with restricted circulation (Fig. 16). We believe the basin depths were euxinic during periods when no reflux currents existed; the early part of the A-1 megacycle was such a period. Otherwise, when

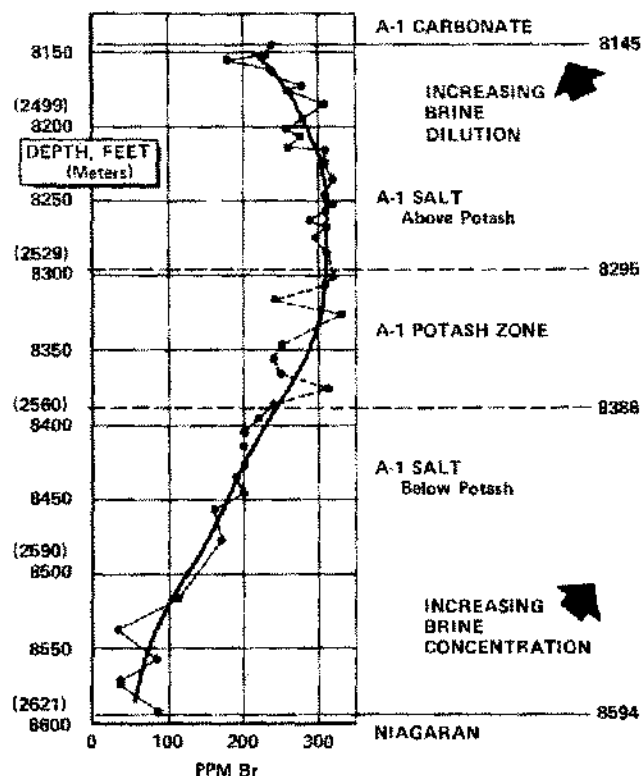


Figure 35. Bromine profile of the A-1 Salt in the Dow #8 Salt—"smoothed" curve.

salt was being deposited and reflux currents had established a basinal circulation, the sinking of the centrally-located, oxygenated, highly saline, surface waters prevented stagnation of the deep basin (Sverdrup, et al, 1946, p. 1087). It should be noted that the younger salts are not known to contain any similar black, sulfurous, shaley beds.

3. There appears to have been no loss of potassium nor bromine ions out of the basin during the first half of the A-1 Salt megacycle. This suggests a large storage space for brine, as we estimate the volume of the resulting sylvinite zones in terms of several cubic miles.

4. The vertical position of the potash (in the upper half of the A-1 Salt) generally conforms with the deep water theory advanced by Schmalz (1969) in which he stated, "... the basin will be half filled with anhydrite and halite by the time the brine . . . becomes concentrated enough to allow the accumulation of the high-solubility salts," (p. 810).

5. The absence of mid-basin potash in salts younger than the A-1, is attributed to us to the early development of reflux currents, in part due to the shallowing of the bathymetric basin with time, but also to the carry-over of "trapped" brines. If late B, D, or F potash deposits exist in Michigan or in the New York-Ohio Salina basins, they will be found in distinctly marginal sub-basins separated

from the main basin, as in the case of the Lower Rhine deposits, not in mid-basin as is the A-1 Potash.

6. The sulfato-deficiency of the Salina evaporites is in part due, we believe, to carry-over of "trapped" halite brines. A "trapped" brine implies storage space, i.e. depth.

7. Even modest slopes require the basin center to be appreciably deeper than the rims; in a 300 mile (480 km) diameter basin a slope of 1 to 1000 results in 800 feet (420 m) of depth.

Rim and edge-basin factors

The identification of carbonate facies equivalent to mid-basin evaporites has not been attempted here. The literature contains a degree of conflicting opinions concerning the relationships between marginal reefs and evaporites and as one moves away from the Michigan Basin out onto the approaches to the evaporite basins of Michigan-Ohio-New York, where evaporites are lacking or poorly preserved, the disagreement over correlations becomes more serious.

1. Gill and Briggs (1970) identified debris found under the A-1 Evaporite to have come from the top of a reef. They call this unit A-Zero. The reef, near the basin edge, is over 400 feet high. Thus, water depths of 400 feet (120 m) over the margins existed for some unknown time before the first evaporite was deposited out near that margin of the basin.

2. The contaminated, non-evaporite fraction of "dirty" salt includes some materials we believe are allochthonous clastics. The clean, inter-bedded salt does not contain transported materials. Many of the clastic beds within the B, D, and F Salts have been traced across Michigan to New York State. We believe the widespread clastic portions are probably windblown, waterdeposited material. But whatever the mode of transportation, we attribute the alternation of clean and "dirty" salt to the presence or absence of a source area; clean salt was deposited when extensive source areas were not available, "dirty" salt when very large source areas were available. The source areas, we believe, were great expanses of sea bottom, out beyond the basin proper which could be exposed to the sun and wind by a slight lowering of sea level. Conversely, a slight rise in sea level could eliminate the source. The approaches to the basin can be expected to show evidence of frequent and large-scale erosional episodes related in time to the mid-basin deposition of "dirty" salt and to many of the non-evaporite rocks of the Salina Group.

The general lack of clastics in the A-1 Salt, A-2 Salt, and the lower parts of the B Salt suggests that there was no important source for clastic sediments (regardless of the mode of transportation) and, therefore, the approaches to the basin were largely water-covered. Reef tops and exposed island arcs were sources for local water-borne clastics but we do not consider them large enough

in areal extent to be a significant source of windblown clastics.

As we have found no clastics associated with the A-1 Potash zone, we conclude that the potash was deposited in mid-basin at a time when the basin rims were largely water-covered.

Perspective

This study was basin-center-oriented and the problems were considered from mid-basin looking toward the margins. Most other workers have studied the shallow-water deposits and erosional features on the rims and looked inward. This different point of view may explain differences of opinion. Certainly there is much yet to be done on Michigan salt and potash.

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