Gamma-Ray Logs and the Origin of Salt

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ABSTRACT

Stratigraphic relationships in the Upper Silurian Salina Group in New York, Pennsylvania, Ohio and Ontario have been determined through a study and correlation of 435 sample and gamma-ray logs. Although the Michigan and Appalachian basins are structurally distinct, nearly identical rock units can be recognized in each. Subsurface units in these basins have been correlated with formations defined from surface exposures.

The Vernon Shale of New York correlates with the Bloomsburg and Wills Creek formations of Pennsylvania and divisions A, B, and C of the Michigan subsurface. The Syracuse Formation corresponds to the Tonoloway and divisions D thru F4. The Camillus and Bertie formations are equivalent to the uppermost Tonoloway and lower Keyser and division F5, F6 and G.

In the Appalachian basin salt beds occur in the Vernon and Syracuse formations. Vernon salts can be traced 300 miles from central Michigan through Ohio and Pennsylvania into central New York. Certain deflections on gamma-ray logs can be traced over 600 miles from western Michigan to central New York. Comparison of gamma-ray logs suggests that thick halite beds formed rapidly relative to the deposition of intervening rock layers, supporting the proposition that basin floor subsidence occurs before the deposition of salt beds. A hypothetical depositional model suggests that salts formed in both shallow and deep water at rates 100 times those of the intervening sediments.

INTRODUCTION

The Salina Group consists of shales, dolomites and evaporites of Late Silurian age that occur in the Appalachian and Michigan basins. This report is a brief summary of the results of a three-year study of the subsurface Salina Group. A more comprehensive and detailed report,[2] including maps and cross-sections, was published by the New York State Museum and Science Service in 1969. Sample logs and gamma-ray logs from about 435 wells drilled for oil or gas were utilized in this study.

STRATIGRAPHY OF SALINA GROUP

Detailed studies were undertaken throughout an area which included parts of New York, Pennsylvania, Ohio and Ontario. This area constitutes the northern end of the Alleghany synclinorium—bounded on the north by the Adirondack dome and Canadian Shield, on the east by folded and metamorphosed lower Paleozoic rocks and on the west by the Findlay and Algonquin arches. The Appalachian basin is structurally distinct from the Michigan basin. However, in the Salina Group nearly identical subdivisions can be recognized in each basin and traced across the intervening arches from one basin into the other.

The stratigraphic subdivisions of the Salina Group recognized in these two basins and their correlation are shown in Figure 1. The Salina Group was originally defined from surface exposures in New York State, but because of the poor quality of these exposures only a partial understanding of

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[2] Stratigraphy of the Upper Silurian Salina Group New York, Pennsylvania, Ohio, Ontario: New York State Mus. Sci. Service, Map and Chart Ser. No. 12.

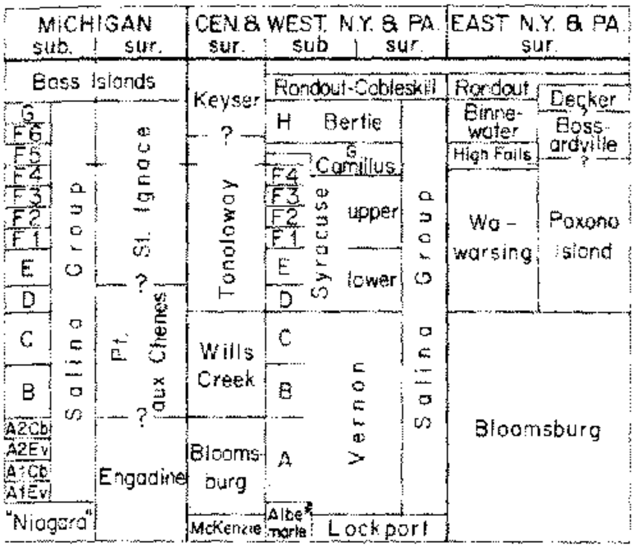

Figure 1. Correlation of surface and subsurface units.

the stratigraphy of the group was developed. In 1945 K.K. Landes published a description of the subsurface Salina Group of Michigan. The sequence of units defined A thru G, with only slight modification, has become the standard for the Michigan basin and for the subsurface Salina Group everywhere. Surface exposures of the Salina Group are relatively few, poor and incomplete. Much more has been learned from the study of subsurface well data over the past 20 years than through the efforts of many geologists examining surface exposures during the preceeding 100 years.

The relationship of Landes' subsurface divisions to formations defined from surface exposures is shown in Figure 1. The type of the Salina Group is in New York State where it consists of 4 formations: the Vernon, Syracuse, Camillus, and Bertie. The group is underlain by the Lockport Dolomite and overlain by the Helderberg or Onondaga limestones. It is 2,500 feet thick in north-central Pennsylvania but in the Michigan basin attains a thickness of 4,000 feet.

The Vernon is a red shale in eastern New York but the lithology changes to green shale, dolomite and even salt in central and western New York. It has a tripartite nature that correlates with the subsurface divisions A, B, and C. To the east it becomes coarser and thicker. It correlates in southeastern New York and eastern Pennsylvania is the Bloomsburg Formation, a large deltaic deposit over 2,000 feet thick. The Wills Creek Formation of central Pennsylvania corresponds to the middle and upper Vernon of New York, the subsurface divisions B and C.

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. The uppermost bed in Unit B is mined at Retsof, New York, 35 miles south of Rochester, in the largest salt mine in North America. This mine has been in continuous operation since 1884.

The Syracuse Formation corresponds to Units D, E, and F of the Michigan sequence. The Syracuse is a mixture of shales, dolomites and salt beds 1,500 feet thick in north-central Pennsylvania. In the Appalachian basin it is the major salt-bearing division of the Salina Group. Approximately 4.3 trillion tons of salt underlie 10,000 square miles of New York State. Eighty percent of this salt is in Unit F.

In Michigan, Unit F has been subdivided into a series of couplets, each couplet composed of a salt bed and an overlying unit of shale, dolomite or anhydrite. Although the salts of Unit F are not continuous from the Michigan basin into the Appalachian basin, the same subdivisions of Unit F can be recognized in the latter area. This is possible because of the unique gamma-ray log signatures of the rock units. Consequently, we now know that the youngest salt beds in the Appalachian basin are those of F5. No salts equivalent to F6 of the Michigan basin are present. However, the non-saline portions of the F5 and F6 couplets are present. These are the Camillus and Bertie formations of New York.

The Syracuse and Camillus formations of New York correlate with the Tonoloway limestone of central Pennsylvania, Maryland and West Virginia. The overlying Bertie is equivalent to the lower portion of the Keyser limestone of that area. The base of the Bass Island of Michigan correlates with the base of the Cobleskill of New York and the *Gypidula prognostica* zone of the Keyser of Pennsylvania. Upper Bass Island may be as young as parts of the Helderberg of New York and consequently would be early Devonian in age.

The salt beds of Unit B will be of interest to geologists seeking the origin of salt. These beds have one outstanding feature—their persistence. Figure 2 indicates the great lateral extent of the 6 salt beds usually encountered in Unit B. Three of these can be traced from Michigan thru Ohio and Pennsylvania into west-central New York, a distance well over 300 miles. The Appalachian basin was not a graben or a long narrow trench. Rather it was a broad basin, connected with the Michigan basin through the Chatham sag in extreme southwestern Ontario. The persistence of these salt beds over such a broad area implies great extent and uniformity of the structural and chemical conditions responsible for the deposition of salt.

A second feature worthy of note is the deflection in the gamma-ray logs labeled "cb", shown in Figures 2 and 3. This deflection in the lower portion of Unit C has been observed on logs of wells in Michigan, Ohio, Ontario, Pennsylvania and New York. It can be traced from western Michigan to east-central New York, over 600 miles. As a stratigraphic marker and probable time-line it can be matched only by the Tioga bentonite of the Middle Devonian.

Salina rock and evaporite units have characteristic, often unique, gamma-ray log patterns that can be recognized over broad areas as suggested by Figure 3. Certain specific deflections can be pointed out as important horizon markers of

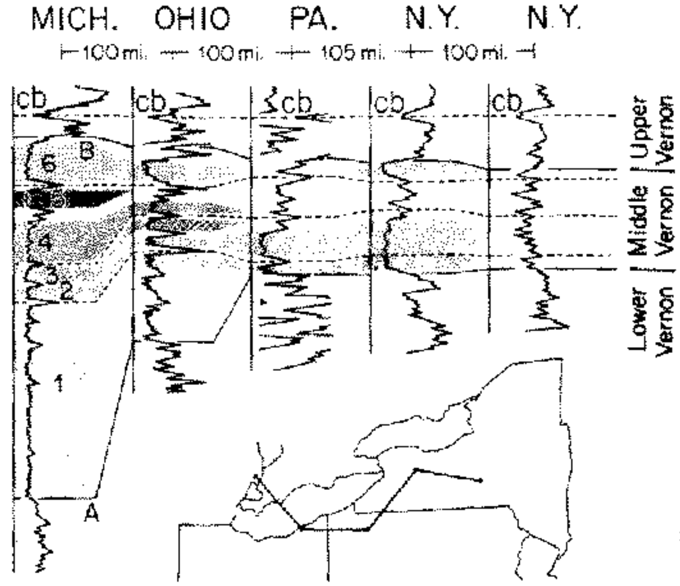

Figure 2. Correlation of salt beds, Unit B.

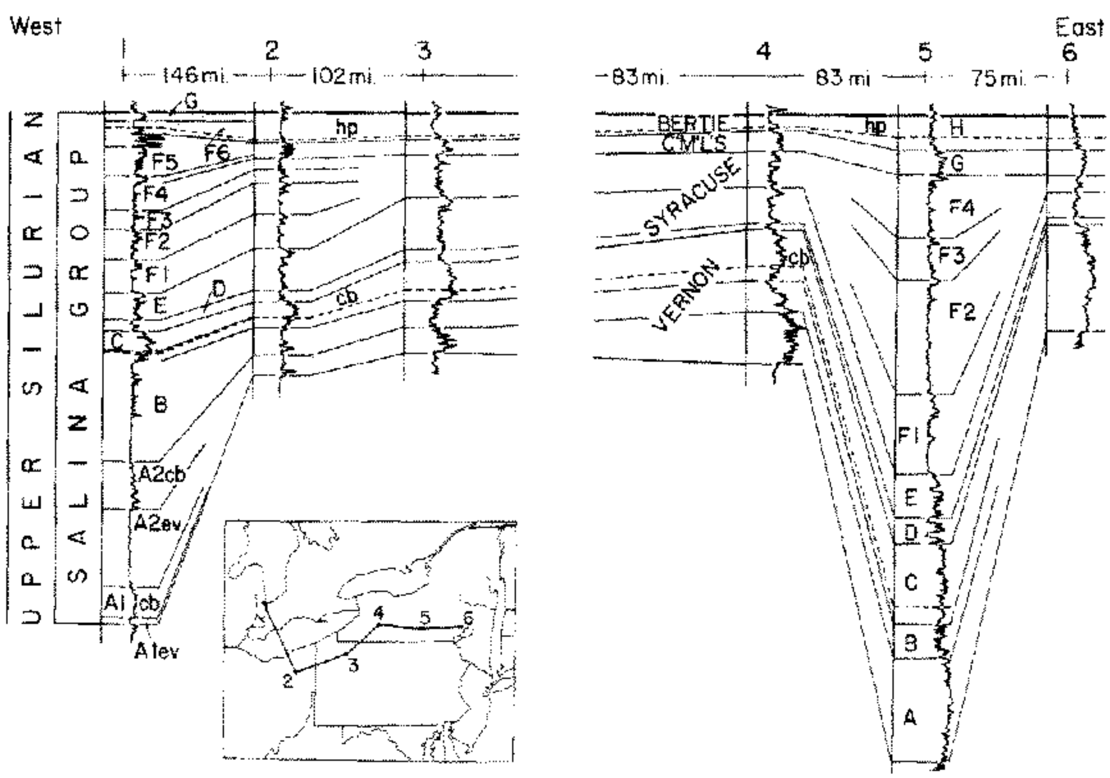

Figure 3. Section–Michigan to Ohio, Pennsylvania, and New York.

widespread occurrence. Consequently, the stratigraphy and inferred geologic histories of the two basins, Michigan and Appalachian, are very similar. Three conclusions seem warranted by these observations: (1) Salina units are essentially time-rock divisions. If they varied in age, it is unlikely that their characteristic or unique patterns would be maintained for such great distances. (2) Both the Michigan and Appalachian basins were in the same climatic zone with few or no important climatic differences between them. (3) This climate must have been the most important factor controlling sedimentation. Events, such as the initiation and cessation of halite deposition, or the formation of such thin beds as horizons "cb" and "hp", seem to have occurred simultaneously in both basins. No factor other than climate appears to have been able to account for the widespread occurrence and uniformity of depositional sequences during Salina time.

DEPOSITION OF SALINA EVAPORITES

Three conditions generally are held essential for marine deposition of the evaporites gypsum, halite and potash:

1. An arid, but not necessarily hot climate. This is required to maintain an adequate rate of evaporation.

2. A depression or basin in which the concentrated brine and precipitates may be collected. The connection between this basin and the open sea or ocean must be more or less restricted by some means—a reef or series of reefs, a bar or sill, a long fetch of very shallow water, or a series of smaller, shallower "fore Basins."

3. An abundant supply of sea water containing the dissolved minerals.

Inasmuch as the amount of salt in sea water is less than 3 percent, tremendous volumes of water must be evaporated to produce a bed of halite several tens or hundreds of feet thick. For example, it has been calculated that a thousand feet of water would yield a bed of salt only 15 feet thick. It seems very unlikely that the initial depths of the basins were large enough to accommodate the entire volume of water necessary to precipitate a thick bed of salt. On the other hand, there is evidence, such as cross-bedding and ripple marks, that has been interpreted to mean that at least some halite is deposited in very shallow water, perhaps not over 10 or 20 feet deep. To reconcile these apparently conflicting ideas geologists have offered two hypotheses: (1) a continuous influx of sea water over the barrier and into the basin during salt precipitation and (2) a continuous subsidence of the basin floor to make room for the accumulating deposits. The first hypothesis remains in good standing but there is a growing body of evidence that many salt deposits did not form in shallow water and that 99 percent of the subsidence of the basin floor takes place before salt precipitation begins.

Richter—Bernberg, Borchert and Muir, following their extensive study of the German Zechstein evaporites of Permian age, concluded that where thick evaporite sequences occur, the major portion of basin subsidence took place prior to the deposition of salt. Halite may accumulate at rates up to 140 mm per yr. For the Zechstein, rates of 20 to 80 mm per yr. have been suggested. In contrast, a rate of subsidence in excess of 1 mm per yr. is considered unlikely except in tectonically very active areas. Values of 0.3 and 0.03 mm per yr. have been calculated for the Gulf Coast and Appalachian geosynclines. One may conclude that, although the overall average rate of sedimentation may be less than or only slightly greater than the rate of subsidence, the initial depth of the basin must be of the same order as the thickness of salt which accumulates within it. What are the alternatives? Increasing the rate of subsidence would require implausibly violent tectonism. Decreasing the sedimentation rate would demand preservation of the essential but delicately balanced climatic, structural and chemical conditions for hundreds of thousands, perhaps millions of years. Neither of these seems to be an acceptable alternative.

Two observations made during this study lend support to this idea that subsidence precedes salt deposition. In Figure 4 the patterns for the salt beds of Unit F, have been deleted from the gamma-ray logs of wells in the center of the basin where many thick salt beds exist. The remaining pattern for such wells is very similar to that of wells at the margin of the basin where salt was *not* deposited. The total thickness of *rock* (non-saline) strata in Unit F in both types of wells is nearly the same despite the presence of hundreds of feet of salt in the deep basin wells. It is suggested, therefore, that the deposition of a salt bed, often scores of feet thick, is an extremely rapid event relative to the deposition of the intervening anhydrite, shale and dolomite layers. If this were not so, one could reasonably expect that some sort of deposition would have occurred in the marginal areas during the supposedly long period of salt precipitation in

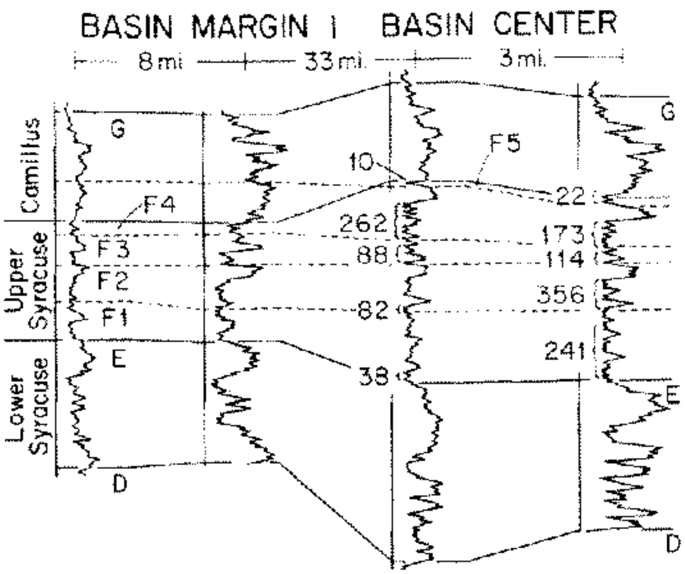

Figure 4. Correlation, margin to basin center.

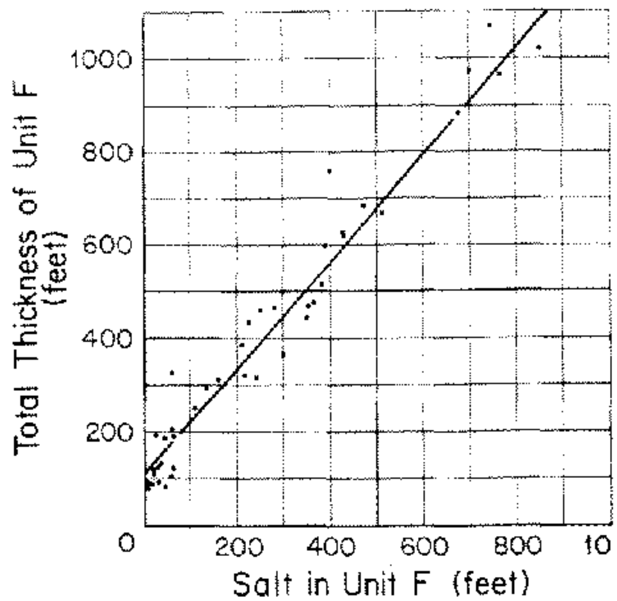

Figure 5. Salt thickness, Unit F.

the center of the basin. Consequently, one could not match gamma-ray logs in the fashion shown in Figure 4. In other words, when salt was being deposited, little or no other sediments were being deposited.

Figure 5 is a plot of the total aggregate thickness of salt in Unit F against the thickness of the unit. This graph indicates that the increase in thickness in Unit F is almost entirely due to the addition of salt. Only 15 feet of non-saline rock is added for every 100 feet of salt.

One may make three conclusions here: (1) It appears likely that the accumulation of thick deposits of salt requires the prior establishment of a basin whose depth is of the same order of magnitude as the thickness of the deposits. (2) The rate of salt precipitation probably was considerably greater than the rates of deposition of the intervening strata. (3) It is also probable that, at least before and alternating with deposition of the salt beds, the sedimentation rates for associated rock strata were significantly less than the subsidence rate. Otherwise, deepening of the basin would not occur and space for thick salt deposits could not develop. An alternative is to infer long periods of subsidence without deposition of any type. This would permit the formation of widespread disconformities in the sequence.

SALINA DEPOSITIONAL MODEL

An attempt has been made to gain some und standing of the quantitative aspects of Sal evaporite deposition through the use of a hy thetical model. Seven walls were selected for tailed analysis: three in the center of Appalachian basin, three near its margin, and c in the center of the Michigan basin.

In each well each lithology was assigned a spe fic depositional rate. Where several lithologies w interbedded an average rate was applied. Calcu tion of the number of years represented by e Salina unit followed. An examination of th initial calculations showed a not unexpected va tion in the length of time determined for each u Inasmuch as each division is a time-rock unit wh boundaries approximate time planes, an appro ate length of time was selected for each unit. depositional rates for each unit in each well w then adjusted to produce this time interval or nearest approach to it. This adjustment resulte the adoption of more rapid average depositio rates for a well near the center of the basin (mm per yr.) than one in a marginal area (0.2 r per yr.). It also suggested the incompleteness of depositional record in the marginal well.

An average subsidence rate was determined and, if reasonable, applied throughout the column at each well. They average 0.2 or 0.3 mm per yr. for marginal wells and 0.3 to 0.9 mm per yr. for wells near the center of the basin. Calculation of the rate of change and amount of change in water depth followed. Assumption of an initial water depth at the site of each well was then made, this assumption in part dictated by the net loss in depth and by the obvious requirement that deposition at no time could proceed above sea level. Calculation of the depth of water at the end of the deposition of each Salina unit was then possible.

The model suggests deposition of the entire Salina Group in about 1.5 m per yr. An estimate of 5 m per yr. has been made from a recent Silurian correlation chart and available radiometric dates. Depositional rates assumed in the model and thought to be reasonable, would have to be reduced to less than one-third their present values to account for such a long period. An alternative—long periods of little or no subsidence or deposition.

The major assumptions made in the construction of this depositional model involve the rates of deposition and subsidence and the initial water depth. Other data are established by simple calculations. Depositional rates for shale, dolomite and anhydrite range from 0.2 to 1.0 mm per yr. In accordance with the theory earlier established—that halite is deposited much more rapidly than the adjacent rocks—a depositional rate of 20 mm per yr. was assumed for salt. This is relatively conservative, compared with rates cited for halite derived by solar evaporation in modern salt pans. Yet it is 100 times the rate frequently assumed for shale and/or dolomite in the depositional model. It yields a calculated evaporation rate of 128 cm per yr. (50 in. per yr.), a rate that also is quite conservative, perhaps more characteristic of temperate than tropic climates.

The water depths calculated for the end of each Salina unit in some of the wells are shown in Figure 6. For the Appalachian basin, a well (long dashes) near the margin of the basin may be contrasted with two wells near the center of the basin (dots, solid line). This graph emphasizes several assumptions made in the development of the model and suggests certain other points. The nearly

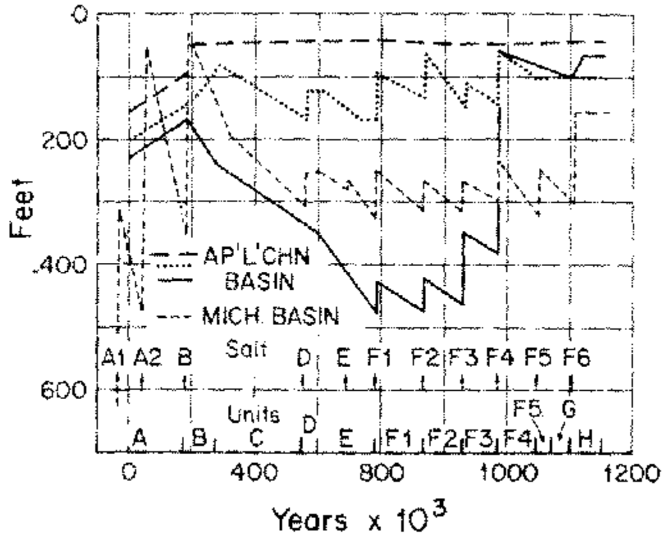

Figure 6. Hypothetical water depths.

vertical segments of each plot emphasizes the rapidity of salt deposition and consequent rapid basin filling. For example, 150,000 years are suggested by the model for the deposition of the F1 couplet. But of this only 1,000 years more or less, is required for salt precipitation. This diagram also suggests that the deposition of thick beds of salt can be inhibited if the basin is too shallow. Note that the F4 salts essentially filled the Appalachian basin. There are wells in which F3 salts perform the same function. Apparently, D, E, or F salts failed to develop in the Appalachian basin because this area remained shallow after filling by B salts. In contrast, the Michigan basin (short dashes) was not filled by F4 salts, leaving space for the additional F5 and F6 beds. Although the model is highly speculative and involves a certain amount of "circular reasoning" it is in keeping with the theories that the deposition of thick evaporite beds requires the prior establishment of a "deep" basin and that salt precipitation proceeds at a rate many times faster than either non-saline sediment deposition or basin subsidence. It suggests that most of the Saline evaporites were deposited in waters 100 to 400 feet deep; possibly as much as 600 feet.