Sabkha Deposition of the Salina Group (Upper Silurian) of New York State

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ABSTRACT

The rocks of the Salina Group (Upper Silurian) of New York are inferred to have been deposited in environments analogous to modern sabkha *environments. Evidence supporting a* sabkha *origin includes: abundant desiccation cracks, sulfate nodules, gypsum crystals and pseudomorphs, halite crusts, flat-pebble conglomerates, abundant erosion surfaces, algal stromatolites, and other structures in the carbonate-sulfate rocks. A few fossil zones are interbedded with the* sabkha *sediments indicating occasional slight transgressions of a restricted hypersaline sea onto the* sabkha. Sabkha *deposition was also interrupted by influx of terrigenous sediments; the terrigenous sediments were, then, gradually superseded by the* sabkhas. *This change probably reflects cessation of uplift in the source area to the east or southeast.*

The salt beds interbedded with the sabkha *sediments are of two kinds; (a) primary and (b) secondary. Primary salt beds formed on the* sabkhas *in the same general setting where the carbonates and sulfates formed. Primary salt beds may have formed as (1) precipitates from periodic flooding of the* sabkha, *(2) precipitates from salinas within the* sabkha *environment, or less likely, (3) as early diagenetic minerals. The secondary salt beds formed in zones of solution collapse. These beds may have formed through the dehydration of gypsum followed by dissolution of salt from adjacent beds by the released water and collapse of the dissolved and overlying beds and, finally, reprecipitation of halite within the collapse zones.*

The sabkha *origin for the evaporites of the Salina Group in New York differs from the barred-basin concepts previously proposed. The present configuration of the basin resulted from differential subsidence in the* sabkha *environment rather than from filling of a previously existing basin with sediment.*

INTRODUCTION

Various interpretations have been invoked for the origin of evaporites. Examples include their precipitation and accumulation in deep-sea basins, in lagoons, on shallow epeiric shelves, in *sabkhas,* or by replacement of preexisting sediments (Schmalz, 1966, 1969; King, 1947; Scruton, 1953; Borchert and Muir, 1964; Shearman, 1966, 1970; Kinsman, 1966, 1969; Butler, 1969; Fuller and Porter, 1969; Friedman, 1972; Kudryavstev, 1971; others). The purpose of this paper is to test which of these hypotheses may hold for one of the classically studied evaporite sections in North America, the Salina Group (Upper Silurian) of New York State (Grabau, 1913; Alling, 1928; Briggs, 1958; Alling and Briggs, 1961; Dellwig and Evans, 1969; Rickard, 1969; others).

The Salina Group of New York consists of four formations (Fig. 1) which are in ascending order: the Vernon Shale, Syracuse Formation, Camillus Formation, and Bertie Formation. Of particular interest are the evaporites contained within the Syracuse Formation; these evaporites include halite and sulfates. Halite occurs interbedded with other lithologies in the Vernon and Syracuse Formations. Sulfate minerals as thin interbeds, nodules, and finely disseminated specks are found throughout the Salina Group.

LOCATION OF STUDY AREA

The area studied is shown in Figure 2. Detailed study of the exposed parts of the Salina Group was carried out in an area roughly bounded by Camillus, N.Y., on the west and Sharon Center, N.Y., on the east. On the south, the boundary follows the embayed strike belt of Silurian strata. The area of outcrop study extends from Latitude 42°50' North to Latitude 43°10' North and from Longitude 74°35' West to Longitude 76°15' West.

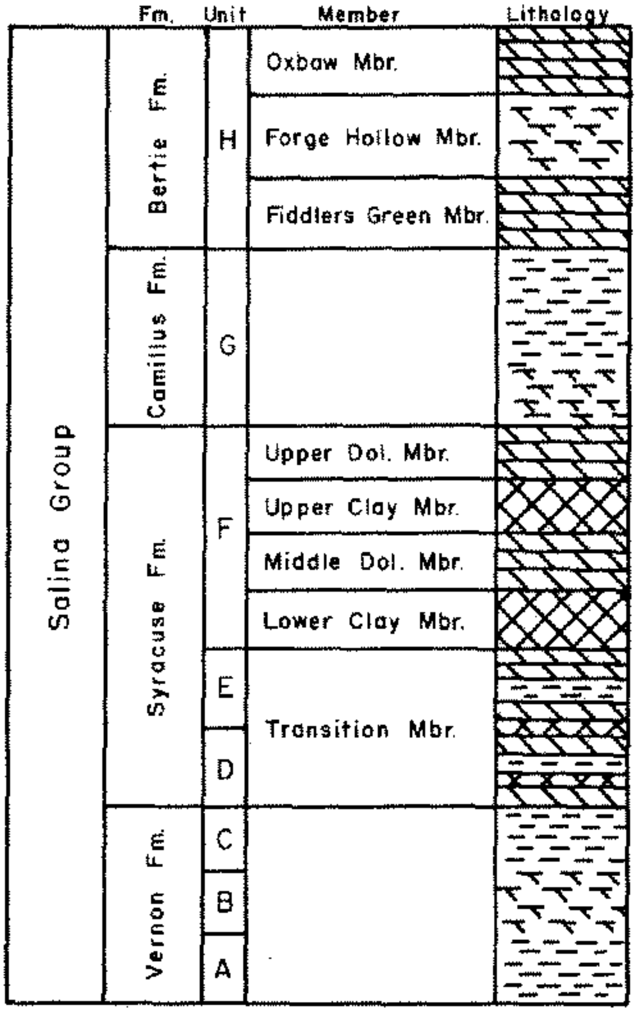

Figure 1. Idealized columnar section showing distribution of lithologies. Letter designations refer to subsurface stratigraphic units. Cross-hatch pattern indicates halite.

Subsurface samples were obtained from the Cayuga Rock Salt Company mine at South Lansing, N.Y., and from a core taken by Morton Salt Company near their mine site at Himrod, N.Y. (Fig. 2). The Cayuga Rock Salt Company mine is located at Latitude 42°32' North and Longitude 76°30' West; the core from the Morton Salt Company was taken at Latitude 42°35' North and Longitude 77°57' West.

STRATIGRAPHY

The Salina Group of New York was deposited during late Silurian time (Cayugan Epoch) in the northern portion of the Appalachian Basin. In most of the outcrop belt the Salina Group is underlain by the Lockport Group (Niagaran Epoch—Middle Silurian); toward the east, however, the Salina Group lies on progressively older rocks (Fig. 3). Throughout the study area the Salina Group is overlain by the Cobleskill Formation. The outcrop of the Salina Group in New York forms an east-west-trending belt up to ten miles wide (Fig. 2). The eastern limit of the outcrop belt is in the vicinity of Schoharie, N.Y. To the west, exposures extend through the Buffalo, N.Y. region into Ontario; west of Camillus, N.Y. (section 22), however, exposures are quite poor and widely scattered.

The Salina Group, as defined by Leutze (1959), for outcrop exposures consists of four formations. These are, in ascending order: Vernon Shale, Syracuse Formation, Camillus Formation, and Bertie Formation (Fig. 1); in the eastern portion of the outcrop belt, the Camillus and Bertie formations grade into the Brayman Shale (Fig. 3). Rickard (1969) recognized these units (with the exception of the Brayman Shale) in the subsurface and established correlations with the Cayugan sequence of the Michigan Basin.

The Vernon Shale, the oldest of the Salina formations, is typically bright red shale but contains local beds or lenses of green shale, dolomite, sandstone, or gypsum. The Vernon reaches its maximum thickness of 500 to 600 feet in the vicinity of Syracuse. The thickness of the Vernon decreases both east and west. In the eastern portion of the study area the Vernon consists of at least 95 percent red shale. This red shale decreases in abundance to the west; near Syracuse the red shales make up about 70 percent of the formation. West of the Genesee River red shales make up less than half of the formation (Leutze, 1964). Salt beds are present near the middle of the Vernon Shale in western New York. This salt is being mined at Retsof, New York. Correlative portions of the Vernon in east-central New York consist of dolomites and dolomitic shales.

Overlying the Vernon Shale is the Syracuse Formation. The Syracuse Formation was originally defined as the salt and interbedded sediments known only in the subsurface (Clarke, 1903). At the outcrop, only the Camillus Shale was recognized. Leutze (1956) redefined the Camillus Shale and applied the term "Syracuse Formation" to the dolomites, shales, and evaporites correlative with the subsurface salt sequence. On outcrop the Syracuse Formation consists of five members, in ascending order: the Transition Member, Lower Clay Member, Middle Dolomite Member, Upper Clay Member, and Upper Dolomite Member. In the subsurface Rickard (1969) recognized three subdivisions (units D, E, and F). Salt beds are present in each of these subsurface units. The salt is interbedded with dolomite and argillaceous dolomite.

The Camillus Shale conformably overlies the Syracuse Formation. The dominant lithologies of the Camillus Shale are red and olive-green shales; the shales occur as massive beds up to 35 feet thick or as interbeds one to three feet thick. Some dolomites and brown shales are present in the lower portion of the unit; mudcracks and

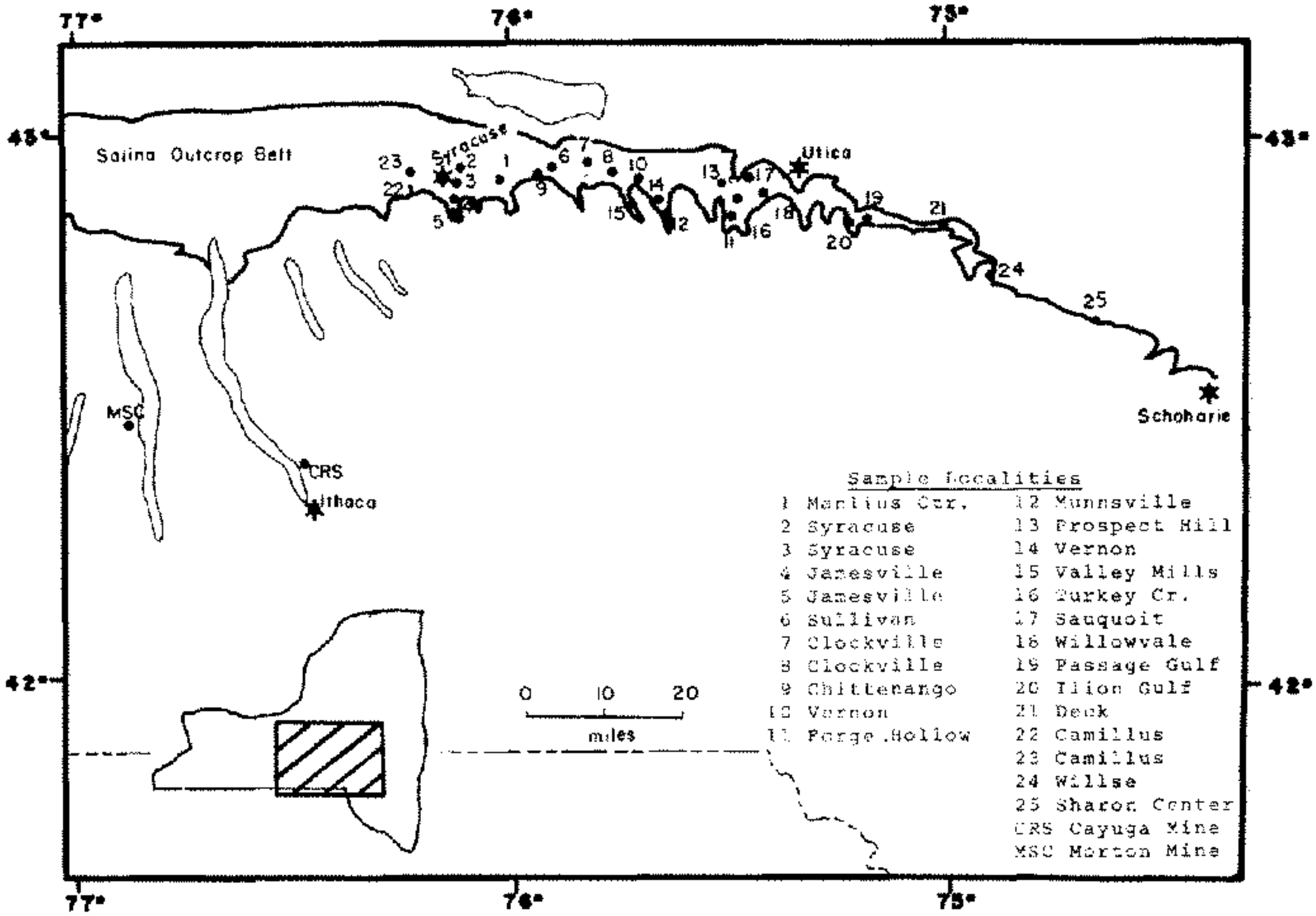

Figure 2. Index map showing location of study area and sample localities.

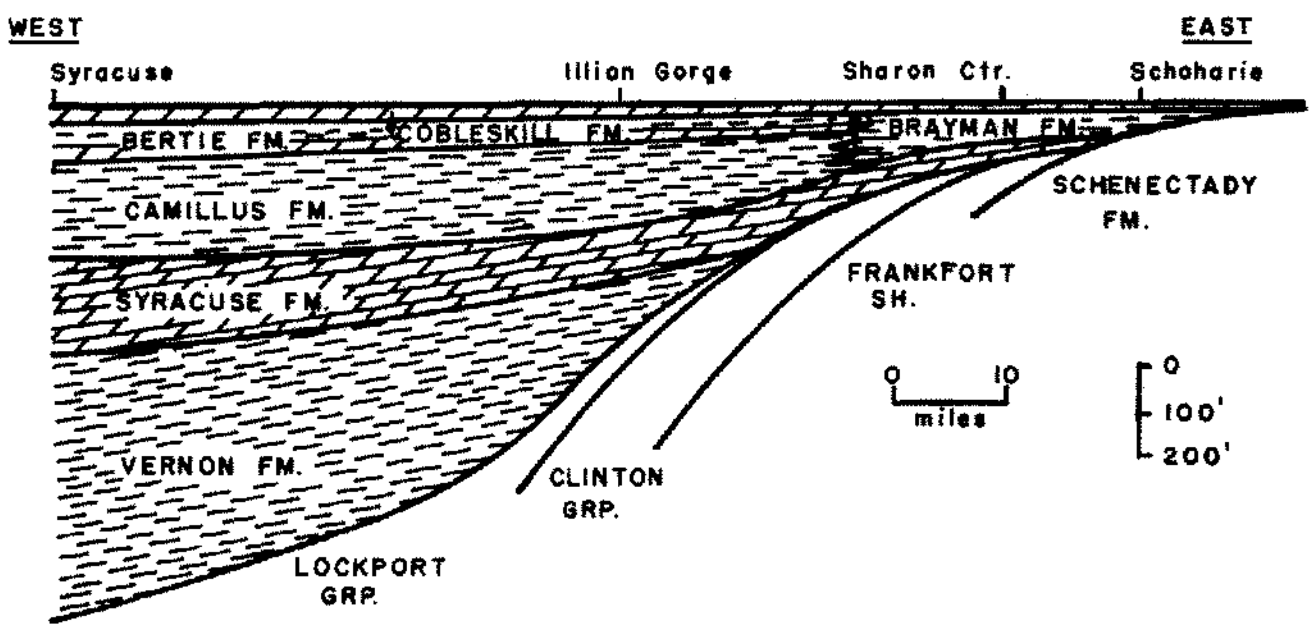

Figure 3. Idealized East-West cross-section through the Salina Group approximately along the outcrop belt. Note the eastward transgressive relationship between the Salina Group and its underlying strata.

ripple marks are common in the dolomite sediments. Many of these dolomites are finely interbedded with gypsum. Quartz sand-rich zones are present throughout the Camillus. The sand content seems to decrease westward. No fossils have been found in the Camillus.

The youngest unit of the Salina Group is the Bertie Formation. In central New York the Bertie contains three members—the Fiddlers Green Dolomite, Forge Hollow Shale, and Oxbow Dolomite, in ascending order. The Bertie Formation is overlain by the Cobleskill Dolomite. The Fiddlers Green Member consists of medium- to thick-bedded, gray to brown, laminated dolomite. Mudcracks and fossils are found at some horizons in this unit. In east-central New York the Forge Hollow Member consists of thin-bedded, finely laminated, brown shaly dolomites. Gypsum crystal molds and interbedded gypsum are common. Mudcracks are abundant on some bedding surfaces. In central and western New York this member contains massive beds of gypsum with interbedded shaly dolomite. The Oxbow Member is a thin- to medium-bedded, light gray dolomite.

In eastern New York the Camillus Formation and Bertie Formation are not distinctive units. The equivalent interval, the Brayman Formation, is represented by argillaceous, greenish-grey dolomites with shaly bedding and a high pyrite content (Treesh, 1972). Well-rounded quartz sand and silt particles occur throughout the unit.

THEORIES OF EVAPORITE GENESIS

Classically, evaporites were thought to form from standing bodies of evaporating marine waters; the standing body of water must be restricted from the open sea so that evaporation can lead to brines of increasing salinity; also, net evaporation for any body of water precipitating evaporites must exceed precipitation plus runoff into the basin. The barred-basin concept of Ochsenius (1877) seems to provide a possible setting for the deposition of evaporites. Adherents of the barred-basin concept form two schools of thought, the "shallow-water" school and the "deep-water" school. The shallow-water model proposed by Scruton (1953) assumes evaporite precipitation in barred estuaries in which a characteristic circulation pattern develops. The circulation pattern results in a distinctive distribution of different salts during precipitation. Ideal conditions for evaporite deposition, according to Borchert and Muir (1964, p. 14), consist of a relatively shallow, marginal sea with only a very shallow, narrow connection with the open sea. The strait from the open sea should ideally contain forebasins in which the sea water undergoes preliminary concentration. Final concentration by evaporation would take place in the marginal basin.

Schmalz (1969) is the most vociferous advocate of the "deep-water" school. Schmalz (1969, p. 809) proposes a model which assumes:

> "the presence of a deep basin, separated from the open sea by a shallow sill and located in a region where climatic conditions favor evaporite deposition. Dense brines, formed at the surface by evaporation, sink to the bottom of the basin where they are trapped behind the barrier sill, and a continuous or intermittent influx of seawater replaces the volume of water lost through evaporation. After a stagnant euxinic phase, the basin is subject to ephemeral and finally permanent deposition of evaporite salts. The latter displace the heavy brines at the basin floor until the basin is completely filled with evaporite salts or until evaporite deposition is ended by a change in climate, interruption of the flow of seawater, or destruction of the basin itself."

Other mechanisms of evaporite precipitation from standing bodies of water have been proposed by Sloss (1969) and Raup (1970); these hypothetical mechanisms could be operative in either deep or shallow basins. Sloss proposes deposition from density layered waters. Such a system could be operative through long periods of time even through intervals of humid climates. Raup suggests that precipitation of evaporites may result from mixing of brines of differing concentration: with this mechanism, precipitation can take place from brines which were undersaturated prior to mixing.

The barred-basin concept has been challenged recently following the discovery that evaporites are forming in sea-marginal supratidal flats *(sabkhas)* in arid climates. Studies of recent sediments along the Persian Gulf in Abu Dhabi have documented the *sabkha* origin of evaporite minerals (especially sulfates) (Shearman, 1966, 1970; Kinsman, 1966, 1969; Butler, 1969). In addition, studies along the Baja, California, coast have revealed deposition of halite in a *sabkha* environment (Phleger and Ewing, 1962; Thompson, 1968; Kinsman, 1969; Phleger, 1969; Shearman, 1970). *Sabkha* evaporite deposition has also been interpreted for many ancient rocks (Kerr and Thompson, 1963; Murray, 1964; Schenck, 1967, 1969; West, Brandon, and Smith, 1968; Shearman and Fuller, 1969; Friedman, 1973).

An unusual view on the origin of evaporites was presented by Kudryavstev (1971). According to Kudryavstev, evaporites originate by metasomatic replacement of sedimentary rocks by different salts. The evidence presented by Kudryavstev has been hotly contested by many evaporite researchers. A replacement origin for evaporites has been suggested by Fuller and Porter (1969) and Friedman (1972). These authors, however, do not advocate metasomatic replacement.

PREVIOUS STUDIES OF NEW YORK SALINA EVAPORITES

Merrill (1893) interpreted the Salina Group salt and gypsum deposits as precipitates from a quiet, standing body of water; this study also traced the interesting history of the salt industry in New York State from the discovery of salt springs by Jesuit missionaries to the sophisticated mining techniques of the period. In another early study, summarized in his monumental textbook, Grabau (1913, p. 378–379) proposes unusual origins for the Salina evaporites. The gypsum, according to Grabau, is an alteration product of impure limestones. Erosion of underlying Niagaran formations supposedly released connate waters in quantities great enough to account for the origin of the Salina salt beds in the Appalachian Basin. The hypotheses of Grabau now seem untenable in light of modern sedimentology; by contrast Merrill's hypothesis shows rather remarkable insight. Many later researchers have come to conclusions which are surprisingly similar to those of Merrill.

Alling (1928) conducted a very good, detailed study of the Salina Group in New York State. Although much of Alling's work has been modified by modern hypotheses, the work stood for many years as the authority on New York Salina rocks; Alling's work is still an important and useful reference for students of the Salina Group. The detailed petrographic analyses are especially useful. Alling was noncommital on the origin of the salt beds within the Salina Group. He did, however, present nine possible hypotheses on their origin; each of these hypotheses was discussed including a discussion of shortcomings of each hypothesis. Many of these hypotheses are similar to those presented in the recent literature on evaporites.

Modern studies of evaporite-bearing rocks in the Salina Group of New York State began with Briggs (1958) who integrated stratigraphic, sedimentologic, and theoretical considerations into a depositional model for Salina evaporites. Briggs modified the models of King (1947) and Scruton (1953) to fit the stratigraphic and sedimentologic data available at the time. Briggs' findings suggested that the Appalachian Basin was connected with an Arctic seaway to the north. However, Briggs' study was regional and did not include detailed sedimentologic analysis.

Alling and Briggs (1961) attempted to establish a regional framework of sedimentation for Salina rocks throughout the Michigan, Ohio, and New York Basins. The framework established, unfortunately, is mostly hypothetical; the postulated fringing Niagaran reef barriers which are essential to the model have not been shown to exist. To the contrary, extensive bordering reefs have not been reported in the Appalachian Basin. In the western portion of the basin Zenger (1965) does report some small bioherms (less than 30 ft vertically and less than 100 ft laterally) from the Lockport Formation (Gasport Member). These scattered, small structures would not provide adequate barriers to the inflow of marine waters so as to restrict a basin sufficiently to produce evaporite mineralization. The Lockport Formation shows a vertical gradation toward more saline conditions and shallower water depths after the reef growth; if the reefs served as a barrier, restriction should have resulted in increased salinities during reef growth not following reef growth.

From a study of salt beds near the middle of the Vernon Shale (Retsof beds of unit B) Dellwig and Evans (1969) proposed that the depositional environment within the Appalachian Basin was shallow and turbulent. Evidence cited for the shallow water include cross-bedding, transported shale balls, and associated fossils. The origin of the transported shale balls is problematical; the armored nature of the shale balls indicates that they may be transported. Fossil evidence of shallow water quoted by Dellwig and Evans is not definitive. Much of their evidence relates to fossils reported by Leutze (1959) approximately 80 miles to the east. Leutze (1959) discussed fossils from the middle and upper Syracuse Formation; the salt beds studied by Dellwig and Evans are several hundred feet lower stratigraphically, in the middle portion of the Vernon Shale (unit B).

In concluding his excellent study of the stratigraphy of the Salina Group, Rickard (1969) applied the Schmalz (1966) model of deep-water, barred-basin deposition to the Salina evaporites. Evidence cited in support of this depositional mechanism involved extremely rapid rates of deposition observed for halite. Applying these rates of deposition to the established stratigraphic framework, Rickard concluded that subsidence of the basin could not have kept pace with the deposition of salt; therefore, the initial depth of the basin must have been of the same order of magnitude as the thickness of salt which accumulated within the basin. Applying this reasoning to the New York Salina evaporites, Rickard (p. 22) concluded that "most of the Salina evaporites were deposited in waters 100 to 400 feet and possibly as much as 600 feet deep."

Preliminary results of the present study have been published as abstracts (Treesh and Friedman, 1973a, b).

Our interpretation on the origin of the evaporites of the Syracuse Formation will be discussed in the next sections under two separate headings, (1) non-salt lithologies and (2) halite lithologies.

NON-SALT LITHOLOGIES

The rocks of the Salina Group in New York consist of salt interbedded with dolomites, argillaceous dolomites, and terrigenous rocks. The salt and its interbeds will be discussed separately in the following sections. Descriptions and interpretations of the rocks interbedded with the salt are discussed in the present section.

Dolomites

Description. Dolomites compose the dominant lithology interbedded with the salt beds in the Syracuse Formation. These dolomites are characterized by mudcracks (Fig. 4), flat-pebbles (Fig. 4), fenestrae (birdseye structures), sulfate nodules (Fig. 5), gypsum crystals and pseudomorphs, algal stromatolites (Fig. 6), microchannels, erosion surfaces, and ripple marks. Most rocks are nearly pure dolomite although dolomitic limestones do occur associated with algal stromatolites. Gypsum or anhydrite are present as thin interbeds in many samples.

A very restricted fauna is present, but rare, in the dolomites. The fauna is dominated by ostracodes but includes locally abundant brachiopods, gastropods, and pelecypods. Most fossils are abraded and apparently represent a transported assemblage.

Origin. The dolomites are interpreted as deposits within a *sabkha* or *sabkha*-like environment (Treesh, 1973). The sedimentary structures and mineral composition of these rocks are similar to those reported from modern *sabkhas* along the Coast of Abu Dhabi in the Persian Gulf (Shearman, 1966; Kinsman, 1966, 1969; Butler, 1969). The composition and apparent transported nature of the fauna are compatible with the interpretation of a *sabkha* environment.

Argillaceous dolomites

Description. This lithology is characterized by a distinctive set of sedimentary structures. These structures include erosion surfaces, mudcracks, and adhesion ripples (Fig. 7). Mineralogically this lithology ranges from argillaceous dolomites to dolomitic shales. Quartz sand and

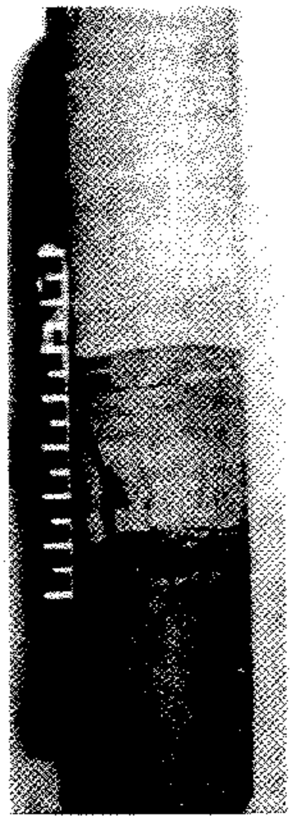

Figure 4. Two zones of flat-pebble conglomerate one of which overlies a surface on which a mudcrack is developed. Sample from core of Morton Salt Company. Transition Member of Syracuse Formation. Smallest scale divisions 0.5 cm.

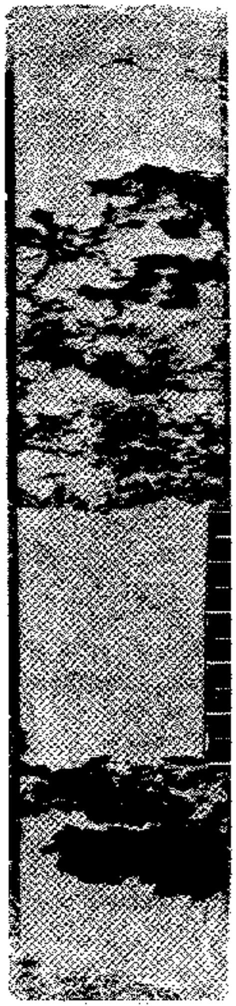

Figure 5. Anhydrite nodules in dolomite. Sample from core of Morton Salt Company. Transition Member of Syracuse Formation.

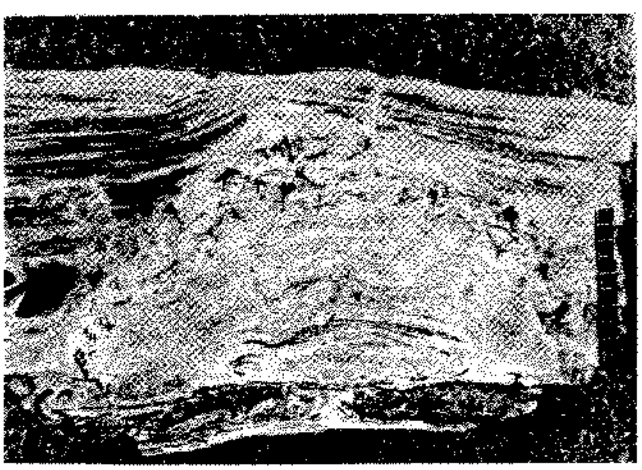

Figure 6. Algal stromatolite from near top of Transition Member in the mine of Cayuga Rock Salt Company. Smallest scale divisions 0.5 cm.

Figure 7. Wispy laminae interpreted as adhesion ripples. Note anhydrite nodules at top and bottom of sample. Sample from core of Morton Salt Company. Transition Member of Syracuse Formation.

silt-grain content is high; the quartz particles are well-rounded and frosted. Some sulfate nodules (Fig. 7) are also present in this lithology. Some gypsum interbeds are present but may be secondary in origin.

Origin. The interpreted depositional environment for the argillaceous dolomites is a *sabkha* environment with a moderately high influx of terrigenous sediments. The argillaceous nature of the sediments in addition to the quartz sand and silt verify the relatively high influx of terrigenous particles. The rounding and frosting of the quartz grains and the presence of adhesion ripples are indicative of eolian transport. Rounding and frosting are typical of eolian quartz; adhesion ripples form by adherence of windblown sediment to a damp surface (Glennie, 1970).

Terrigenous rocks

Description. Although a few sandstones are present, the terrigenous rocks consist predominately of shales. Red and green shales are most common although some gray and black shales are present. Most shales are massive and only a few are fissile; dolomitic shales are common. Although some kaolinite was found in red shales, illite is the dominant clay mineral. The red shales of the Vernon contain very angular quartz silt. The only sedimentary structures found in these shales are mudcracks, which are abundant in many exposures.

The sandstones are gray or green in color. Bedding varies from massive to thin. Some cross-beds have been observed. Mineralogically, well-rounded, frosted, medium-grained quartz sand particles are the dominant constituents. Dolomite and clay-mineral content of the sandstones are often quite high.

Origin. The shales are interpreted as deposits of rivers of low gradient flowing into a shallow sea. The red coloration of the rocks may have been formed in the source area prior to deposition or may result from oxidation in the depositional environment. Rapid burial of the sediments preserved the original color of the sediments. Most of the quartz in the shales occurs as angular silt-size particles. Alling (1928) demonstrated convincingly the similarity of the quartz silt with that of modern deltaic deposits. The few rounded, frosted quartz-sand particles in the shales are probably of eolian origin. The sandstones of this lithofacies contain rounded, frosted quartz, some of which is cross-bedded. These sands may have resulted from eolian reworking of the finer-grained sediments.

The source area of the sediments was east or southeast of the study area (Hoskins, 1961). The general westward fining of the sediments and decrease of content of terrigenous sediment to the west support this interpretation.

HALITE LITHOLOGIES

The salt beds within the Salina Group in New York are restricted to the Vernon and Syracuse formations. On the basis of bedding characteristics, relationship to overlying and underlying units, and inclusions, these salt beds can be subdivided into two kinds: (1) laminated and (2) nonlaminated. Although much of the Salina salt appears to have flowed, most salt beds can be assigned to one of these kinds of salt.

Laminated salt

Description. As demonstrated by analyses of water-insoluble residues halite makes up 85 to 98 percent of the laminated salt by weight (Table I). The laminated salt occurs as individual salt beds; nondeformed salt beds range in thickness up to 33 ft. These beds consist of alternating light and dark layers. On close examination, the dark layers are relatively inclusion-rich, whereas the light layers are relatively inclusion-poor. The thickness of the layers averages 1 to 3 inches.

Inclusions within the halite, which define the layers, consist predominately of anhydrite. Although they are less abundant than anhydrite, dolomite and quartz are present in all samples. Illite, chlorite, calcite, feldspar, and talc are also present. Examination of water-insoluble residues with binocular and optical microscopes reveals that the anhydrite occurs as sand-size, slightly rounded, euhedral crystals; the dolomite occurs as discrete lithoclasts which are also slightly rounded and of sand size. Many freshly broken samples from this lithofacies give off a strong odor of H_2S.

Another distinctive feature of this lithofacies is the presence of large, rounded dolomite-anhydrite clasts; the maximum dimension observed for these clasts is 12 inches. Layers above and below these large clasts have been deformed; the layers below have been compressed whereas those above drape over the clasts (Fig. 8). Smaller dolomite-anhydrite clasts are concentrated within the same horizons as the larger clasts.

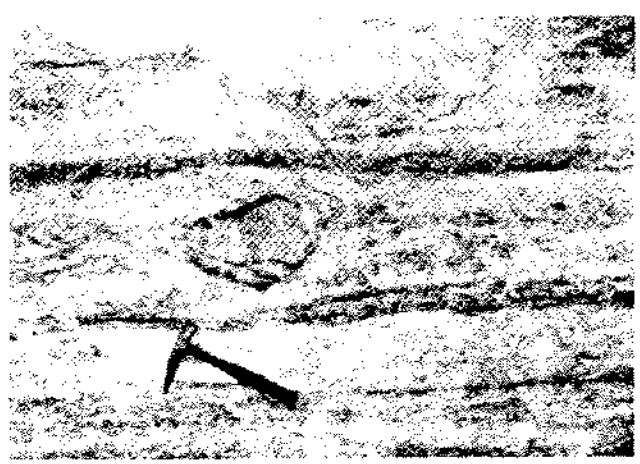

Figure 8. Draping of halite laminae around dolomite clasts in Transition Member of Syracuse Formation in mine of Cayuga Rock Salt Company.

Table I

Analyses of Water-Insoluble Residues of the Salt

Sample	Strati-graphic Unit	Litho-facies	% Insol.	Anh.	Dolo.	Qtz.	Clay	Cal.	Other
CRS-1	D	L	1.4	90%	5%	2%	2%	—	F'spar, talc
CRS-2	D	L	2.6	92%	4%	2%	2%	—	—
CRS-3	D	L	2.7	93%	2%	3%	2%	—	—
CRS-4	D	L	3.2	91%	3%	3%	3%	—	—
CRS-5	D	N	31.0	—	—	—	—	—	—
CRS-6	D	N	9.3	A	S	A	?	—	Sylvite
1957	D	N	7.7	A	S	T	—	—	—
1936.5	D	L	9.5	A	A	S	—	—	—
1922	D	L	2.5	A	—	—	T	T	—
1900	D	N	4.5	A	S	S	—	—	—
1867	D	N	7.2	A	S	T	—	—	—
1806	E	L	0.6	A	S	T	—	—	—
1700	F	N	1.9	75%	12%	7%	5%	1%	—
1568	F	N	2.9	A	A	S	T	?	—

A = Abundant
S = Some
T = Trace

L = Laminated salt
N = Non-laminated salt

The salt appears to have been completely recrystallized. Evidence supporting this conclusion includes the large size of the salt crystals and the distribution of inclusions. Most crystals of salt are large, ranging in diameter up to 1 inch. These crystals have grown together in an interlocking framework. Because the inclusions are commonly distributed along crystal boundaries rather than uniformly within, the crystals apparently expelled inclusions during recrystallization.

Some salt beds display evidence of flowage. The flowage is most evident in the mine of the Cayuga Rock Salt Company in the basal F salt beds (Syracuse Formation). Two salt beds with an interbedded dolomite-anhydrite bed have been deformed by flowage of salt on the crest of the Portland Point Anticline (Prucha, 1968). Flowage is also evident in the salt bed at the top of unit D (Syracuse Formation) in the Cayuga mine. The flowage at this level is best illustrated by breakage of a kimberlite dike which intrudes the salt. Small-scale recumbent folds are also present in this salt zone. The salt zone in the core of the Morton Salt Company from 1723 to 1561 ft also appears to have flowed. In this core the dolomite clasts are rounded, and the salt is highly recrystallized and appears to be thoroughly homogenized. Many zones with abundant dolomite-anhydrite clasts are present; these clasts may represent interbeds within the salt which have been brecciated during flowage (Chute, 1972).

The flowage complicates recognition of sedimentary structures within the salt zones. Within the salt bed at the top of unit D in the Cayuga Rock Salt Company mine are structures which may be truncation surfaces; laminae within the salt beds appear to truncate against these surfaces. Some questionable cross-bedding is also present within the salt zone.

The basal contact of beds of the laminated salt is gradational from the underlying units. Most upper contacts are sharp. In many places salt appears to have partially replaced a previously existing sediment.

Origin. The depositional environment for the laminated salt is less obvious than for most non-salt lithologies. The major reason for the uncertainty concerning its origin is its highly recrystallized nature. The recrystallization destroys details necessary for a confident interpretation. Nevertheless, associated facies strongly indicate that the salt was deposited on brine-logged, carbonate-sulfate mud flats analogous to intertidal and supratidal areas. Several possible depositional mechanisms are discussed below.

Some indications of sediment transport are present. These include the rounding of the anhydrite and dolomite fragments, concentration of dolomite-anhydrite clasts along certain horizons, possible truncation surfaces, presence of quartz and other terrigenous minerals, and questionable cross-beds. If these features do indeed indicate sediment movement, then the laminated salt may represent a reworked salt deposit; reworking could be accomplished by either wind action or by brines saturated with halite. Glennie (1970, p. 139) reports eolian reworking and transportation of halite in the Rann of Kutch, India. Reworking by wind or water, however, fails to explain the lamination and strong smell of H_2S in this lithology.

The laminae within the laminated salt are defined by inclusion-rich zones which alternate with relatively inclusion-free zones. The dark inclusion-rich zones contain abundant dark opaque material. Analyses of water-insoluble residues indicate the presence of 0.44 to 2.14 weight percent organic carbon. The residues are lacking in palynomorphs or organic entities with cellular organization which might indicate the source of the organic carbon. Freshly-broken samples are fetid; the H_2S may result from reduction of anhydrite and/or decomposition of organic matter.

The presence of organic matter indicates several possible depositional mechanisms. The salt may have been deposited by periodic flooding of an extensive carbonate-sulfate mud flat by a few inches to a few feet of hypersaline brine. The organic matter could have been brought in by flood waters or may have resulted from algal mats living on the mud flat. The flooding of this flat by brines concentrated in NaCl might result in precipitation of halite. Dolomite-anhydrite clasts and rounded anhydrite crystals could be transported onto the flat at the same time. Phleger (1969) reports deposition of halite from brines blown onto sea-marginal flats in the Ojo de Liebre Lagoon area, Baja, California. Halite as much as 10 ft thick is present and closely associated with organic material and wind-blown terrestial sediment.

Alternatively, halite may be replacing another mineral in an algal-stromatolite sequence. Fuller and Porter (1969) suggest a possible replacement origin for banded halite deposits of the Middle Devonian Winnepegosis salt beds. No petrographic criteria indicative of extensive replacement were found, therefore, this hypothesis is considered less likely than primary precipitation of the salt over algal mats but, as noted previously, the intense recrystallization has destroyed many details of the rocks.

The odor of H_2S might also result, in part, from bacterial reduction of sulfate minerals. The lamination of the salt may be explained by alternating precipitation of sulfate-rich and halite-rich sediments; the sulfate-rich sediments would produce the dark laminae and the halite-rich the light laminae. An environment in which such deposition could take place might be a very shallow (probably less than 10 ft) standing body of hypersaline water (a salina) which is periodically freshened. During the freshened periods the sulfate-rich laminae would be deposited. Burial of the sediments would place them in a reducing environment. Friedman (1966) noted evidence of reduction and production of H_2S from a few feet beneath the salina at Salt Flat Graben, Texas. The fact that the water body must be shallow is indicated by the close association of *sabkha* sediments.

Regardless of the origin of salt beds, the fact that they have flowed and recrystallized is quite evident. Evidence of flowage includes folding of dolomite-anhydrite interbeds, homogenization of salt beds, rounding of clasts, breakage of the kimberlite dikes, and brecciation of apparent interbeds. The recrystallization probably occurred at the time of flowage of the salt. The flowage of the salt may have resulted during development of the Appalachian folds.

Non-laminated salt

Description. Although some beds are a cloudy pinkish color, the non-laminated halite, unlike the laminated salt, lacks internal layers and tends to be clear. The non-laminated salt occurs in beds ranging up to 29 ft in thickness and in secondary veins cutting through the host rock.

The non-halite portion of this lithofacies consists of dolomite-anhydrite fragments, dolomite-anhydrite interbeds, anhydrite crystals, and traces of sylvite. The dolomite-anhydrite fragments are quite angular; they display no rounding. In places fragments can be rotated to fit with adjacent fragments (Fig. 9). This is especially true at the contacts of the non-laminated salt beds with overlying rocks. Fragments such as these have not been transported great distances. The anhydrite crystals are slit-sized and euhedral. These anhydrite crystals are not rounded; they appear to have grown in place. Sylvite in minor amounts is present in some of the pinkish-colored beds.

The water-insoluble content is variable for the non-laminated salt but is consistently higher than for the laminated salt (Table I). The insoluble content varies directly with the amount of clasts present. In samples of non-laminated salt no smell of H_2S is present.

Halite occurs between laminae in some beds adjacent to the non-laminated salt. The nature of the interlaminar halite indicates that during its crystallization the laminae have been pushed apart by the halite.

The occurrence of non-laminated halite in veins also suggests displacement by crystal growth. Many of the veins obviously displace the host sediment. In other cases, the vein-filling appears to be fracture-filling halite with no displacive growth.

Origin. Non-laminated salt beds are apparently secondary (post-lithification) in origin as suggested by the large, clear, relatively inclusion-free halite crystals and by the "fit" of the dolomite-anhydrite fragments. Inclusion-free halite probably did not form in the depositional envi-

Figure 9. Fit of separated dolomite fragments (light) in a halite matrix (dark). Sample from core of Morton Salt Company. Transition Member of Syracuse Formation. Smallest scale divisions 0.5 cm.

ronment. Convincing evidence comes from the displacive nature of the interlaminar halite and halite veins and the lack of association with other lithologies. The means by which the salt was precipitated is much less clear. Conclusive evidence as to its specific origin is lacking and the hypotheses are, therefore, mostly speculative.

Borchert and Muir (1964, Ch. 9) discuss one possible mechanism. They suggest that the water derived from the conversion of gypsum to anhydrite in the subsurface will act to dissolve adjacent halite beds. The resulting NaCl-rich solution with some sulfate remaining in solution might then move upward where it replaces overlying potash salts with halite and anhydrite. Several lines of evidence support this mechanism. First, Stewart (1949) has shown that much of the sulfate in evaporite sequences is deposited as gypsum. Evidence from the present study supports this conclusion. Conversion of this primary gypsum to anhydrite would release 0.486cm^3 of water for every cubic centimeter of gypsum converted. This large potential amount of water would have a substantial effect on the surrounding rocks; it probably dissolved large quantities of halite. The halite-rich brine formed during dehydration of gypsum and solution of adjacent halite could then move vertically through the sediments. The brine may form beds and veins of salt in two ways. First, the brine might replace beds of potash salts as suggested by Borchert and Muir (1964, p. 115). The pinkish color of some beds of the non-laminated salt and traces of sylvite seem to suggest this mechanism. Alternatively, halite may precipitate in zones of collapse within the sediment column. If the water is removed conversion of gypsum to anhydrite reduces the volume of the resulting sediment considerably (Bundy, 1956). Reduction in sediment volume might result in collapse and brecciation of the overlying beds. The brines produced by dehydration could move into the collapse zone and precipitate halite and minor amounts of anhydrite; precipitation might occur contemporaneously with collapse resulting in breccia fragments which appear to be "floating" in the salt. Possibly, a brine-mixing mechanism such as that proposed by Raup (1970) might initiate the precipitation of halite. Another mechanism resulting in precipitation might be from cooling of the brines as they move upward; the cooling of the brines decreases the solubility of NaCl. The decrease in solubility would result in the precipitation of salt from concentrated brines. The solution-collapse hypothesis explains the presence of slightly rotated angular dolomite fragments. Each of these hypotheses explains some of the characteristics of these beds. It seems possible that both mechanisms could be operative in the study area.

ENVIRONMENTAL RECONSTRUCTION

The Salina Group of New York State is a transgressive sequence. Each stratigraphic unit is more extensive than the preceding unit (Fig. 3). The Salina Group transgressed onto a subaerially-exposed carbonate and clastic mud flat. The underlying Lockport Formation shows a vertical tendency toward increased salinity, shallowing, and general restriction (Zenger, 1965). In the eastern portion of the study area the Lockport Formation is represented by the Ilion Shale. Stratigraphic and lithologic relationships indicate that after the Ilion Shale stopped being deposited a period of erosion occurred. Possibly this period reflects an uplift in at least the eastern portion of the study area.

The youngest Salina unit, the Vernon Shale, resulted from marine, deltaic sedimentation of fine-grained sediment; the sediment was supplied to the marine environment by rivers draining an area of moderately low relief to the east or southeast. The Vernon Shale is, at least partially, correlative with the deltaic Bloomsburg Formation of Pennsylvania. Vernon Shale deposition transgressed eastward across the eroded earlier Silurian and

Ordovician sedimentary rocks (Fig. 3). West of the study area, the Vernon Shale grades into carbonates and sulfates probably reflecting the lack of supply of terrigenous sediments to that area.

Periods of decreased sediment supply during sedimentation of the middle Vernon Shale (unit B) resulted in *sabkha* sedimentation. The middle Vernon Shale along the outcrop belt contains some dolomite interbeds reflecting this decreased sediment supply. In western New York salt beds are present in the middle Vernon Shale (Retsof beds). Salt deposition may have occurred as the result of the decreased inflow of freshwater allowing increasing salinities and, eventually, precipitation of halite. In the east, the freshwater influx, however limited, prevented halite deposition or accumulation.

Deltaic sedimentation ended with the Vernon Shale. However later periods of increased influx of terrigenous detritus occurred during deposition of the Camillus Formation and the Forge Hollow Member of the Bertie Formation. The dominant sedimentary environment for the Salina Group, excluding the Vernon Shale, is a *sabkha*-like environment. *Sabkha* sedimentation was only periodically interrupted. The interruptions of *sabkha* sedimentation were the result of an influx of very shallow marine waters. These marine waters allowed the establishment of a restricted marine fauna. Two faunal zones in the Syracuse Formation and another in the Fiddlers Green Member of the Bertie Formation represent these marine influxes.

Sabkha deposits consist of dolomites and argillaceous dolomites with abundant sulfate minerals. Sedimentary structures and bedding characteristics of the dolomites, argillaceous dolomites, and sulfates are similar to those of modern *sabkhas.* Halite was also deposited in this *sabkha* in one of several ways; the most likely mechanisms of deposition involve precipitation of halite from very shallow (maximum of a few feet) hypersaline waters flooded onto the *sabkha.*

Previously proposed origins for the deposition of halite in the Appalachian Basin require a topographic basin in the environment of deposition. This interpretation is not compatible with the observed facts. The present configuration of the Appalachian Basin does not reflect the topography of the basin at any one time, instead, higher rates of subsidence in the "basin-center" resulted in thicker sediment accumulation than in "basin-margin" areas. It is suggested, then, that the present distribution of the Salina sedimentary rocks reflects a structural basin which lacked contemporaneous topographic expression.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Dr. Lawrence V. Rickard for helpful discussions and for review of earlier versions of this paper. Dr. Newton Chute helped gain access to the cores of the Morton Salt Company. In addition, Cayuga Rock Salt Company is acknowledged for permission to sample within the mine at South Lansing. Morton Salt Company kindly provided one long core which was studied in detail. Dr. John E. Sanders read the manuscript and provided useful criticism.

Financial support for the senior author was provided by two Grants-in-Aid of Research from the Society of Sigma Xi and a Penrose Bequest Research Grant from the Geological Society of America.

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