

# Salt Mining and Possible Future Problems in the Cayuga Lake Region:

## Integration of public-domain seismic with known salt geology

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## Summary

The extension of the Cayuga Mine to the north will encounter a thinned section of the carbonate rock that has been the stable rock unit overlying the Salina Group. This will result in more unstable geological conditions for the mining operations as it extends to the north. The dominant weakening process is the penetration of undersaturated waters driven by ice-sheet flexure.

It is recommended that a full review of all available data, including company-acquired data and salt core, be thoroughly and independently evaluated to quantify risks involved in expanding mining too much further within permitted reserves, or in extending the current mine lease northward beyond the permitted reserves.

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## Introduction

This report defines possible geologic problems that need to be considered before the planned extension of the Cargill Cayuga Salt Mine is approved. To better define the geology beneath Cayuga Lake and north of the current mine area, existing public domain seismic data and outputs are integrated with the known salt geology of the mine and the surrounding areas. Using seismic to define layering in a sedimentary basin is a well-understood methodology in wide use by the hydrocarbon and mining industries and allows broad-scale understanding of the geology in undrilled or un-mined areas.

Results presented in this report are to the best of our knowledge the first use of seismic from the public realm to refine our understanding of the extent and style of the layered geology beneath Cayuga Lake. Previously, the Mullins seismic data from the 1990s was used to study Pleistocene sediment fill in the lakes (Mullins et al., 1996). The NYSERDA-funded Scholz 2002 seismic study was shot in order to shed light on hydrocarbon opportunities at the level of Trenton Black River Fm. However, penetration was not robust to that level, and thus the study was not brought to full completion.

## Seismic

To generate a seismically-scaled model, formations likely to be encountered below Cayuga Lake are cross-referenced to the geological layers encountered in Corehole #18. The location of the Corehole # 18 is 2.5 km from the Cayuga Lake shore.

Formations and thicknesses encountered in the well have been combined via seismic markers to facilitate reliable comparison to the coarser-scale resolution inherent in seismic reflectors. The term “Carbonate Beam,” so defined, consists of Cherry Valley Formation (near Onondaga Limestone) to base Bertie Formation. The rock lithologies are mainly carbonate rocks, which are known from regional salt mining geology to provide a rigid overlying framework in the geologic section above the Salina Group. The latter is composed of softer units with lower mechanical strengths and is made up mostly of interlayered evaporite and shale units. For seismic interpretation, this interval is termed the Evaporite section.

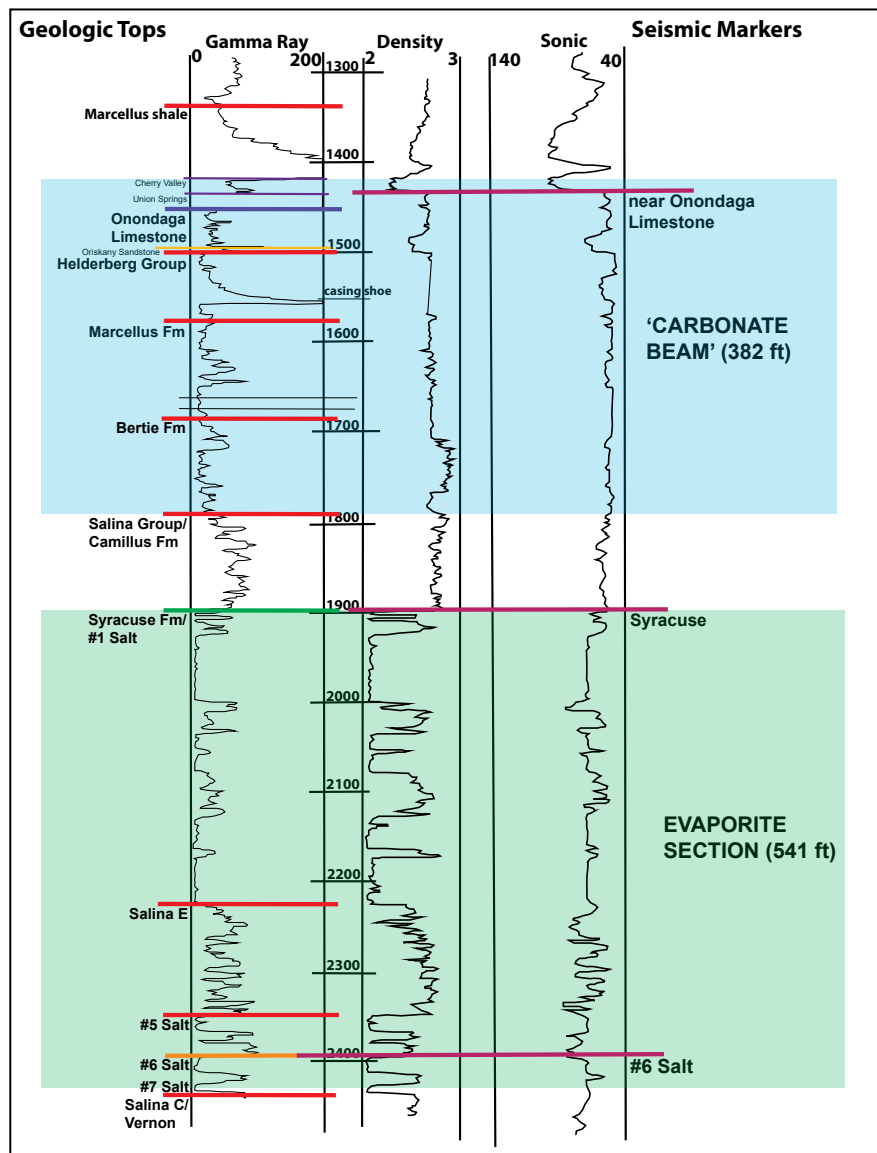


Figure 1. Seismic scale units, based on the geology intersected in Corehole 18. This borehole is the stratigraphic test well drilled to define geological conditions at the proposed lake-side position of Shaft #4.

The thickness of the Carbonate Beam in Borehole 18 is 382 feet, and the Evaporite section is 541 feet. Our evaluation of geological stability will assume that where the carbonate beam section is reduced or breached due to erosion, there will be an increasing risk of geological instability for mining in the underlying Evaporite section. This assumption is based on the documentation of decreased mechanical strength and water entry seen in other areas with similar geology (see geology section).

The basin depression that now hosts Cayuga Lake was formed by glacial scouring of the bedrock and later partially infilled of the valley by glacial sediments. This same process of glacial scours also created the other lakes of the Finger Lakes region (Mullins et al., 1996.) In many places below Cayuga Lake, our seismic analysis shows this has resulted in a downcutting of the Carbonate Beam section along the thalweg of the Cayuga Valley.

### *Seismic documents downcutting*

Seismic analysis in this report uses three different methods to show that the carbonate beam is eroded by the glacial valley in the <sup>1</sup>thalweg of Cayuga lake and that the position of this erosional trace beneath the northern parts of Lake Cayuga increasingly cuts into the Evaporite Section, including portions of the ongoing northern extension of the Cayuga Mine.

1 Thalweg is defined as a line connecting the lowest points of successive cross-sections along the course of a valley or river.

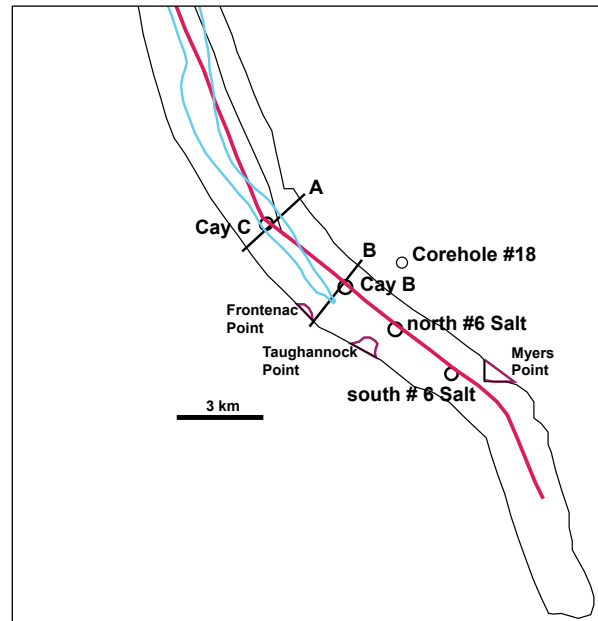


Figure 2. Onondaga subcrop in blue from Ferguson, 2017 and profile locations from Spectra Environmental Group, 2000.

Three methods are used to show that the carbonate beam is eroded by the glacial valley in the thalweg of the Cayuga lakes.

The first method, as outlined in Ferguson 2017 and Ferguson and Warren 2017, maps the outcrop of the Onondaga Limestone along the Cayuga Lake valley floor. The bathymetry of lake water and thickness of glacial sediments above the bedrock was mapped by Mullins et al., 1996. When these contours are converted to feet mean sea level (ft msl), they can be compared to the regional structure

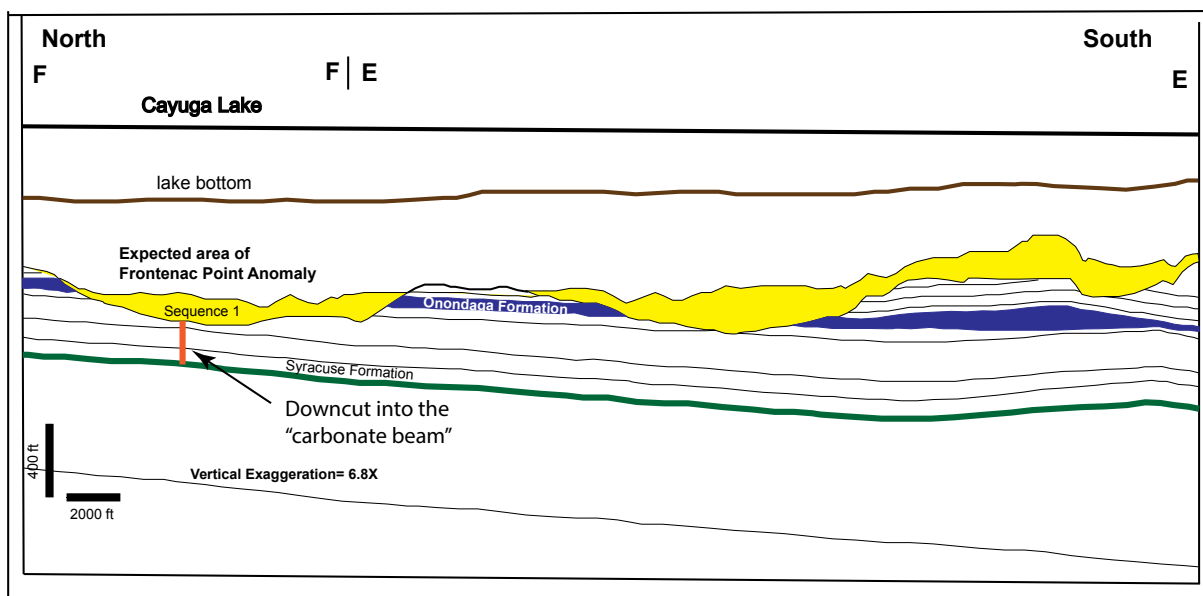


Figure 3. Profile F-E summarized from Spectra Environmental Group 2000 report.

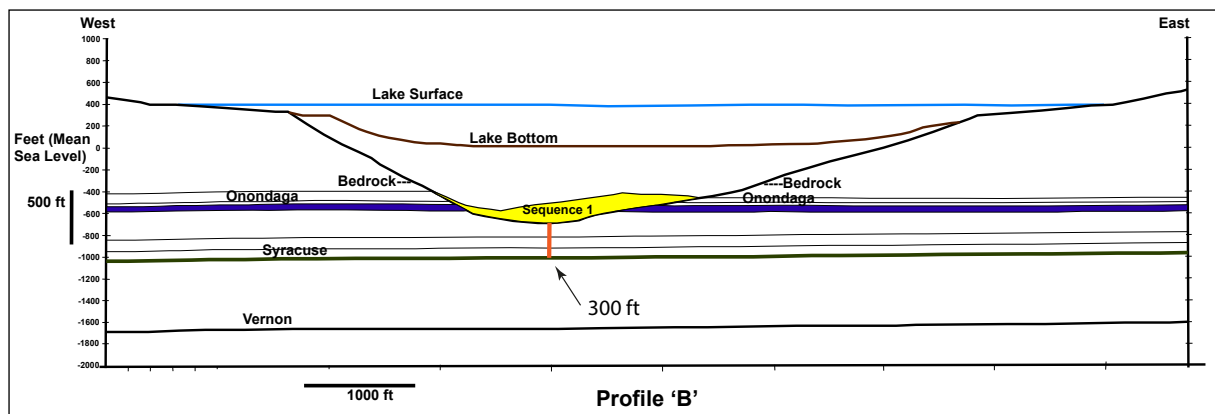


Figure 4. Profile B. Carbonate beam and Camillus Formation downcut to 300 ft.

map of the near Onondaga Formation, mapped as Cherry Valley Formation, by Spectra Environmental Group, 2000. The Cherry Valley Formation is 25 feet above the Onondaga Limestone in Corehole # 18 (Figure 1). The resulting area, shown in blue in Figure 2, is the trend of eroded Onondaga Limestone along the valley floor. The area of reduced carbonate beam is inside the blue line.

Corehole # 18 was drilled about 3 km away from the subcrop of the Onondaga Formation in the Cayuga Valley floor. This seismic indication of direct connection with Pleistocene aquifers of Lake Cayuga was reported in Ferguson, 2017 as a possible reason for the Corehole # 18 encountering a water zone in the Oriskany Formation which is 55 feet below the top Onondaga Limestone.

The second method is to use the profiles generated in a study by Spectra Environmental Group (2000) and which utilised information from a Sear-Brown study (2000). Profiles are based on seismic acquired from 1995 to 1996 for the operators of the Cayuga Mine. The actual seismic data were not placed into the public realm and could not be

loaded and tested in this report. This is one of a number of examples where critical data have been collected but are not available for public use more than a decade after collection.

The along-valley Profile E-F in Figure 3 shows two areas of erosion of the carbonate beam at the Onondaga level indicated by the blue line. This was reported in Ferguson and Warren, 2017.

Further profiles from the Spectra Environmental Group, 2000 are shown in Figure 4 as Profile B and in Figure 5 as Profile A. The Profiles are projections across the valley, with locations shown in Figure 2. Profiles A and B demonstrate significant erosion cutting into the carbonate beam along the deeper parts of the valley floor. In Profile B, which is near the Frontenac Point Anomaly, the section above Syracuse Formation is reduced to 300 feet as indicated by the vertical orange line in Figure 4.

The profile to the north in Figure 5 illustrates an even greater amount of erosion of the carbonate beam, with the result that there is only 80 feet above the Syracuse Formation as indicated by the

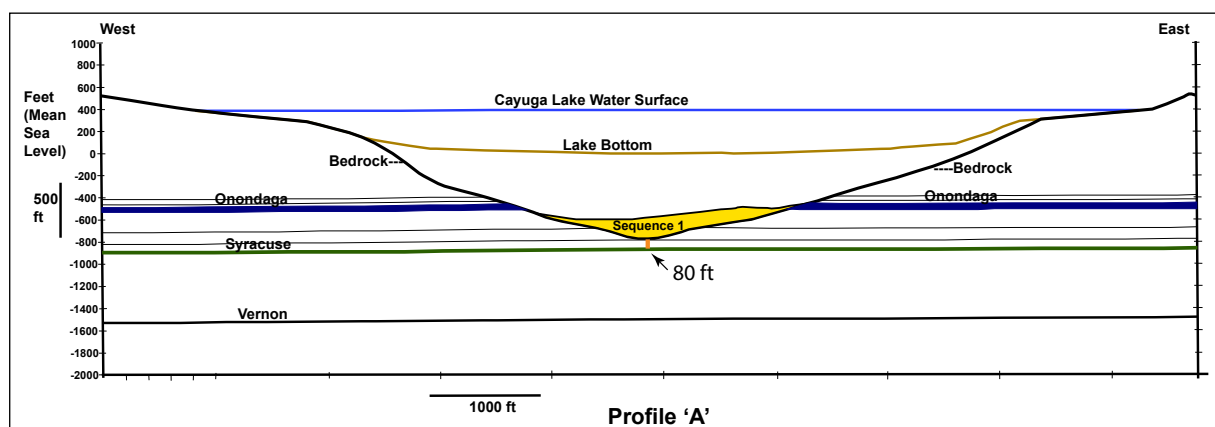


Figure 5. Profile A. Carbonate beam and Camillus Formation downcut to 80 feet.

vertical orange line in Figure 5. This would mean that the carbonate beam has been eroded out and only weaker shales of the Camillus Formation now sit above the evaporite unit.

A third method is to interpret the Cayuga 3 seismic line acquired in 2002 and reported in Scholz, 2006. The seismic SEG Y data have been loaded into a seismic interpretation workstation. The original seismic has been improved by applying a seismic attribute termed structural oriented filtering to improve the signal to noise ratio.

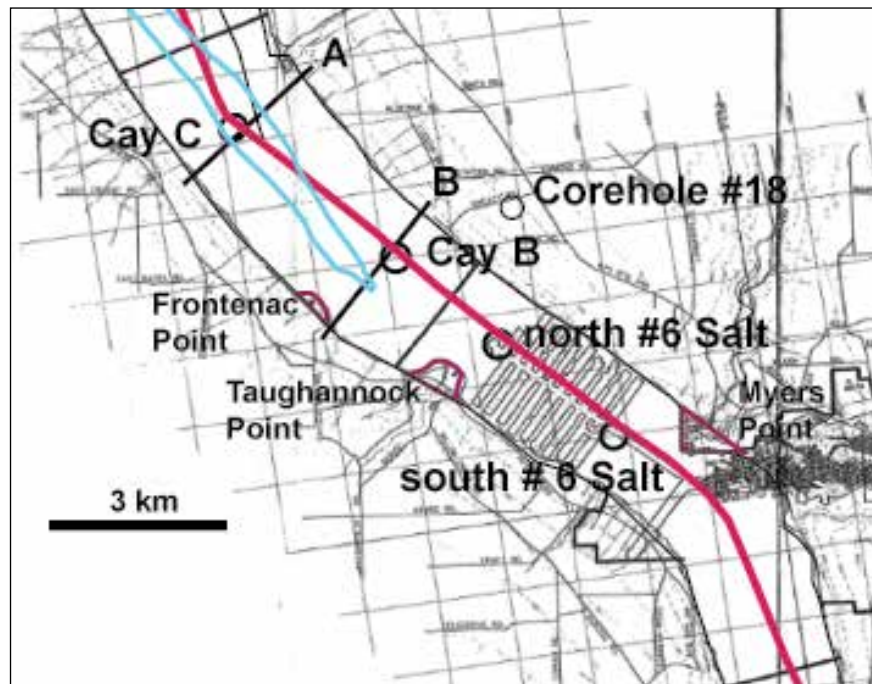


Figure 6. Red line is 2002 seismic Cay3 line. Seismic anomaly extent labelled as south #6 salt and north # 6 salt. Map from Spectra Environmental Report, 2000 shows in black the #6 salt mine footprint in 2000. Location of Profiles A and B from Spectra Environmental Report, 2000 in black.

Seismic reflections in the image are due to the combination of changes in rock density and velocity. This is termed the acoustic impedance which is calculated by multiplying the velocity value at a particular depth by density of the rock. Seismic reflections result from a change in acoustic impedance from a top layer to a lower layer such as occurs at a lithological boundary. The electric well logs for Corehole # 18 in Figure 1 have been reviewed and used to quantify an estimate of the main seismic zones that this geological layering will create in the predicted seismic reflections.

### *Quantifying the seismic layers*

The water bottom is an increase in acoustic impedance due to the change from water to sediment. This is a peak on the 2002 seismic outputs.

The next major seismic reflection below the water bottom will be the glacial sediment to bedrock interface, which is also a peak on 2002 seismic.

The top of the carbonate beam at near Onondaga Limestone would be an increase in acoustic impedance and be a peak on this seismic. This reflection is located at the sediment to bedrock interface in many areas.

The start of the mainly evaporite section is a reflector denoted by a decrease in acoustic impedance and so is a trough on seismic output. This denotes the Syracuse Formation top.

The shale zone in the evaporite unit in Salina E level creates an increase in acoustic impedance, and so is a peak. The evaporites below that seismic level consist of #5, #6 and #7 salt layers and in combination create a decrease in acoustic impedance and so are indicated by a trough in the 2002 seismic. All these reflections depend on the frequency of the seismic data.

A unique anomaly, first identified in Ferguson, 2017, is that the #6 salt level has been observed on seismic. The anomaly location is plotted in Figure 6 as north #6 salt and south #6 salt. The seismic anomaly in the 2002 seismic matches the mine location as shown in Figure 6 (outlined in black as the #6 salt mine footprint). This confirms that the seismic anomaly is the cavity formed by the removal of the #6 salt level which was actively being mined at the time of the 2002 seismic acquisition.

By using the known depth of the #6 salt layer from regional structural maps in the Spectra Environmental Report 2000, the time from the seismic line and the depth points can be used to calculate



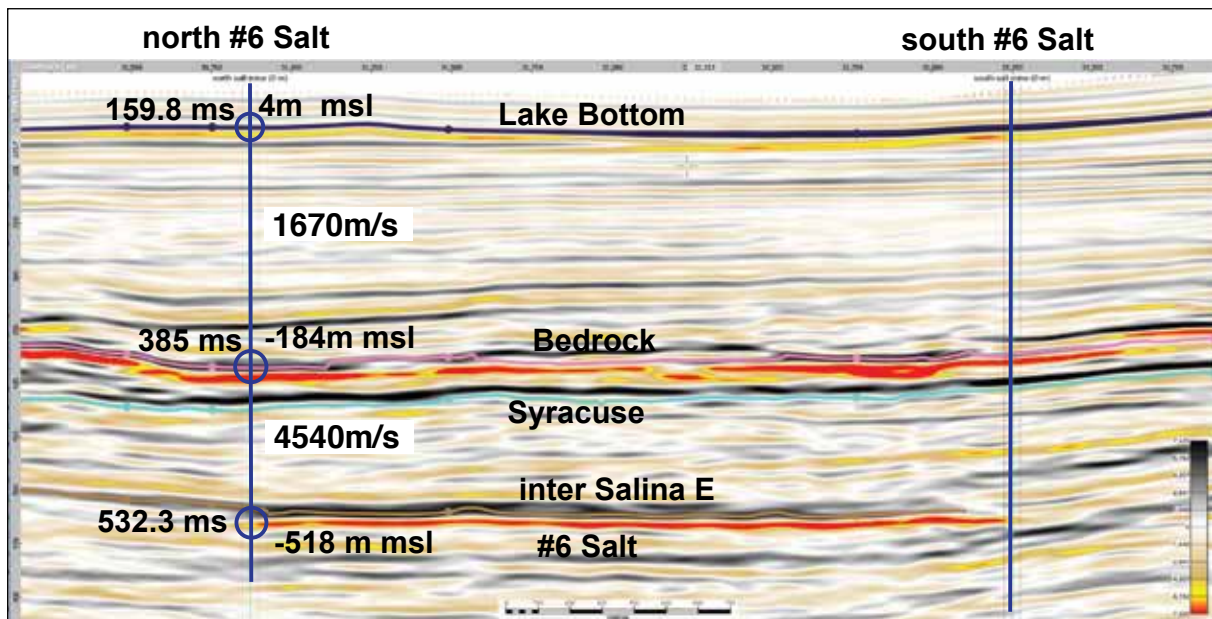


Figure 7. #6 salt level imaged on seismic as a trough- in red. General calculations of velocities shown using the measured time and depth values

a general interval velocity for the rock layers. This is a generalised method as more detailed seismic velocity information is not available in the public domain.

The time to depth points and the calculated interval velocities are shown in Figure 7. The lake bottom depth values are from Mullins, 1996. The value of 1690m/s (5540 ft/s) was calculated for the total lake bottom sediments, which extends from lake bottom to bedrock. This value is within the reported velocity range of 1500 to 2100 m/s for glacial sequences I to VI in Mullins et al., 1996.

The calculated interval velocity of the section from top bedrock to top #6 salt level is 4540 m/s (14900 ft/s). This covers both the carbonate beam and evaporite zones, so it is considered a general velocity value. The Carbonate Beam would have a higher velocity than the Evaporite Section.

The top Syracuse seismic horizon pick is expected to be a trough on the 2002 seismic and is mapped as the light blue horizon in Figure 7 and Figure 8. There is also a more regional seismic reflection above the #6 salt level that projects into an inter Salinas E level, which is mainly a shale unit.

The seismic line in Figure 8 extends to the north. It demonstrates the problem with the 2002 seismic where there are multiples and sideswipe areas. This especially occurs in areas where the seismic line was not shot over the thalweg of the valley

floor. As the line drifted to the valley sides, the valley floor is shallower and has the appearance of an anticline. As illustrated in Figure 8, the Syracuse Formation does not extend to the north and appears to merge with the bedrock floor. The horizontal section at Y between Cay B and Cay C has been correlated to the section at X in Figure 8.

The Salina E horizon is shown in brown in Figures 7 and 8 and is used as a marker for the near #6 salt horizon, since the #6 salt anomaly is no longer evident away from the mined section. It is expected that the more recent seismic would identify the extent of more recent mining of the #6 salt level.

#### *Seismic indicates problems in the north*

There is a thinning of the bedrock to top Salina E from the south to north. This agrees with the previous two methods and confirms a thinning of the carbonate beam overlying the evaporite unit in a northern direction. The exact thinning is difficult to calculate due to the general velocity values used. The amount of thinning is 27 ms in seismic two-way time. This would roughly calculate as 61 m or 200 feet using the 4540 m/s interval velocity. It is expected that the accuracy of these values can be significantly improved if the seismic velocity data become available, or more seismic surveys are used.

The extension of the Cayuga Mine to the north will encounter a thinned section of the carbonate rock that is considered the more mechanically stable



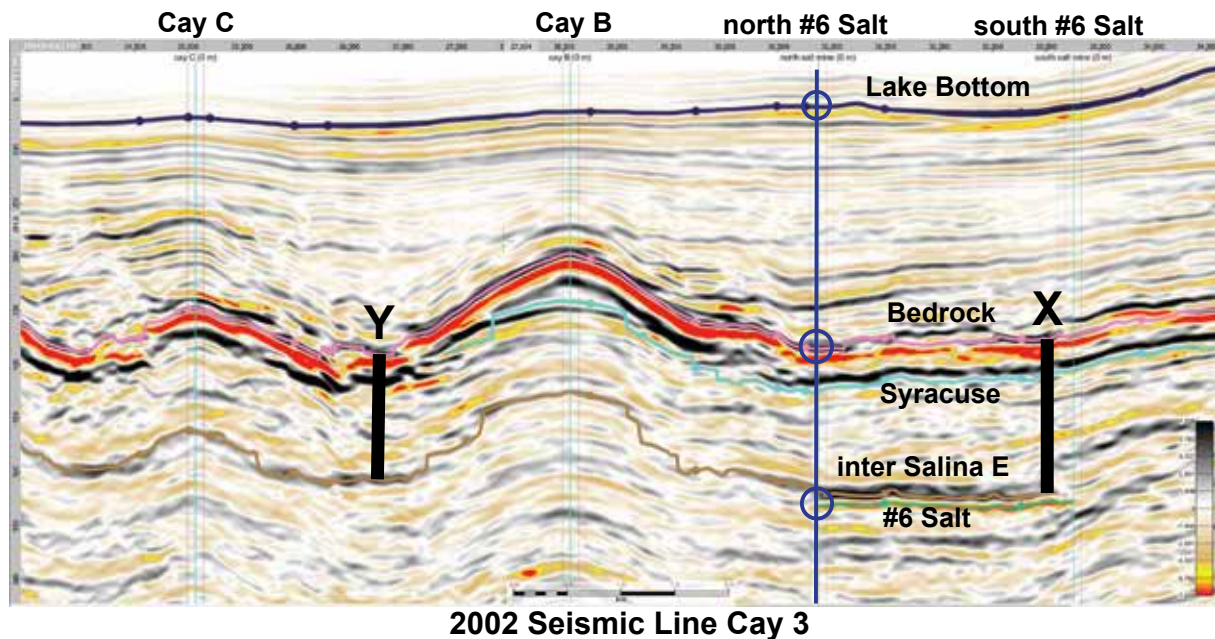


Figure 8. Seismic with horizons- thinning of carbonate beam to north, Loss of Syracuse formation

formations overlying the Salina Group. This thinning will result in more unstable geological conditions for the mining operations. It is recommended that a full review of all available data including company acquired seismic data be used to fully evaluate the risks associated with extending the mine to the north.

### Geology of salt anomalies in Cayuga Lake

Before discussing the relationship between lake geology and seismic anomalies indicative of downcutting, thinning and groundwater connections with the evaporite section, we should compare and contrast the concepts of seismic anomalies, as used in the previous section, and salt anomalies. The concept of salt anomalies is the basis for defining salt problems in salt mines worldwide and will be applied in the following sections (Warren 2017).

An anomaly indicates the unexpected. A seismic anomaly indicates an unexpected change in the velocity of sound waves passing through, or reflecting off, various rock layers. Typically, a seismic anomaly indicates the changes in subsurface rock velocities in a zone of pores and cracks filled with gas. Change may be due to: 1) Hydrocarbons stored in pore space between sand grains: this is the typical situation in oil and gas exploration. 2) Changes in volume of fluids in zones of fractured

rock (this approach would be useful in the interpreting the zone below and adjacent to Cayuga Lake, but requires the acquisition of a dense 3D seismic volume covering the lake and adjacent land area. It cannot be done using available public domain data. 3) An anthropogenic cavity created in a rock, such as a liquid-filled solution storage cavity, or an air-filled mine cavity in salt (this study). 4) Loss of expected seismic unit continuity due to downcutting and dissolution (this study).

An anomalous salt zone is broadly defined as a region in a salt body with atypical features- it can warn of possible mining problems (Warren, 2017). Salt anomalies relate to unexpected changes in: 1) Texture; Coarse-grained, piokiloblastic, friable, mechanical strength, 2) Inclusions; passage into non-evaporite sediments, enrichment in hydrocarbons, brine, gases. 3) Structures; sheared salt, gas outbursts, brine leaks, excessive mine roof and wall slabbing, unexpected ore thinning, rapid closure, jointing, voids, and slight porosity development. 4) Composition of salt unit: Potash/magnesium levels, high anhydrite content (dissolution related fractionation), very black salt (due to disseminated fluid and solid impurities).

Any documented salt anomaly is a warning that the salt geology is changing (for a variety of reasons) and we are entering a location or situation where the mine or borehole may unexpectedly pass out of the salt mass. Passage out of the salt

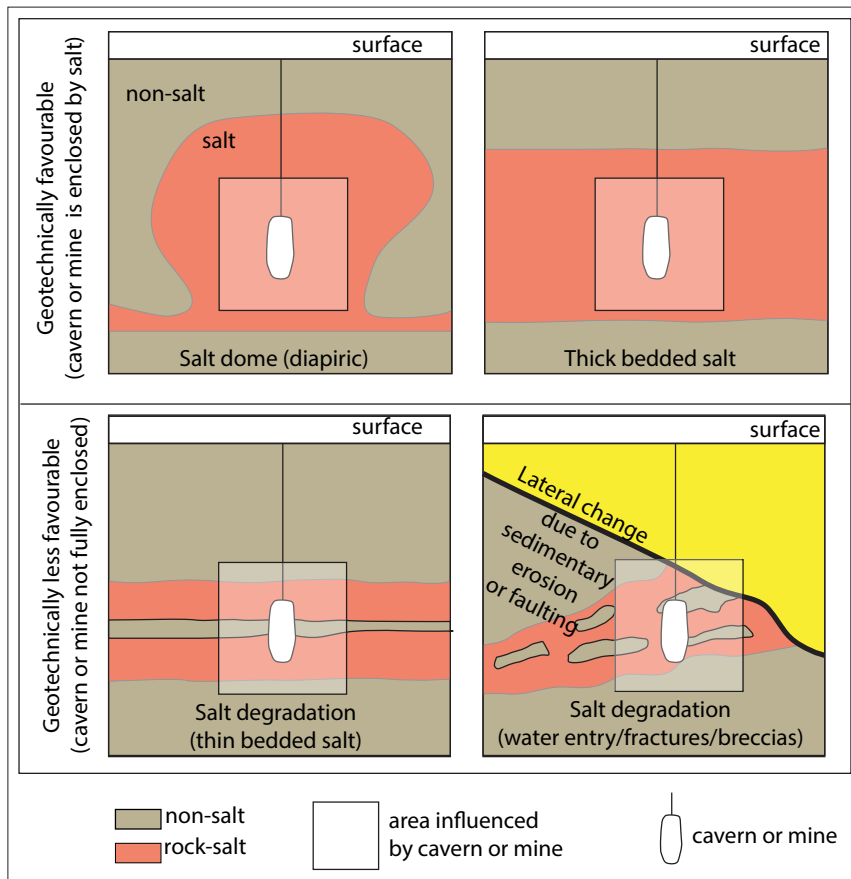


Figure 9. Schematic illustrating the concept of “Stay in the Salt.” (after Warren, 2017)

increases the likelihood of unexpected changes in mechanical stability and water entry into the mine workings. This underlines the simple concept of “stay in the salt” for safe salt mining (Figure 9).

### *Glacial processes drive the thinning of the Carbonate Beam*

Our seismic analysis shows the dominant process controlling the thinning of the carbonate beam beneath Cayuga Lake is glacial erosion with subsequent filling of the down cut glacial valley with sediment. The salt geology of Cayuga Lake is docu-

mented in Warren (2016a, b).

Aspects relevant to the thinning of the carbonate beam and water entry into the Evaporite interval (at the seismic scale) are discussed in this section. Cayuga Lake is one of the Finger Lakes of central New York State. The Finger Lakes are a group of eleven elongate, glacially-scoured lake basins located along the northern margin of glaciated Appalachian Plateau (Figure 10a). All the lake basins are still filling with lacustrine sediment. The base of southward flowing ice sheets eroded the future lake depression into a substrate made up of relatively undeformed, but well-jointed, Devonian sedimentary rocks, which dip gently to the south-southwest (Figure 10b).

The seven larger, eastern Finger Lakes (Otisco, Skaneateles, Owasco, Cayuga, Seneca, Keuka, Canandaigua) form a radiating pattern that projects northward into the eastern basin of Lake Ontario, whereas the four smaller, western Finger Lakes (Honeoye, Canadice, Hemlock, Conesus) project northward to a point near the city of Rochester (Figure 10).

Lake	Length (km)	Width (km)	Elevation (m msl)	Water volume ( $10^6 \text{ m}^3$ )	Surface area (SA) ( $\text{km}^2$ )	Drainage area (DA) ( $\text{km}^2$ )	DA/SA	Maximum depth (m)	Max sedt. thickness (m)	Erosion below lake level (m)	Erosion rel. sea level (m)
Conesus	13	1	249	157	14	168	12	18	n.a.	n.a.	n.a.
Hemlock	11	1	276	106	7	96	14	29	149	173	103
Canadice	5	1	334	43	3	32	11	27	68	94	240
Honeoye	7	1	245	35	7	95	14	9	n.a.	n.a.	n.a.
Canandaigua	25	2	210	1,640	42	407	10	84	202	261	-51
Keuka	32	3	218	1,434	47	405	9	57	146	193	25
Seneca	57	5	136	15,540	175	1,181	7	186	270	442	-306
Cayuga	61	6	116	9,379	172	1,870	11	132	226	358	-242
Cwasco	18	2	217	781	27	470	17	52	95	140	77
Skaneateles	24	3	263	1,563	36	154	4	84	140+	255	8

Table 1. Finger lake dimensions, sediment fill, glacial scour depths and water volume statistics (after Mullins et al. 1996) See figure 9a for lake locations

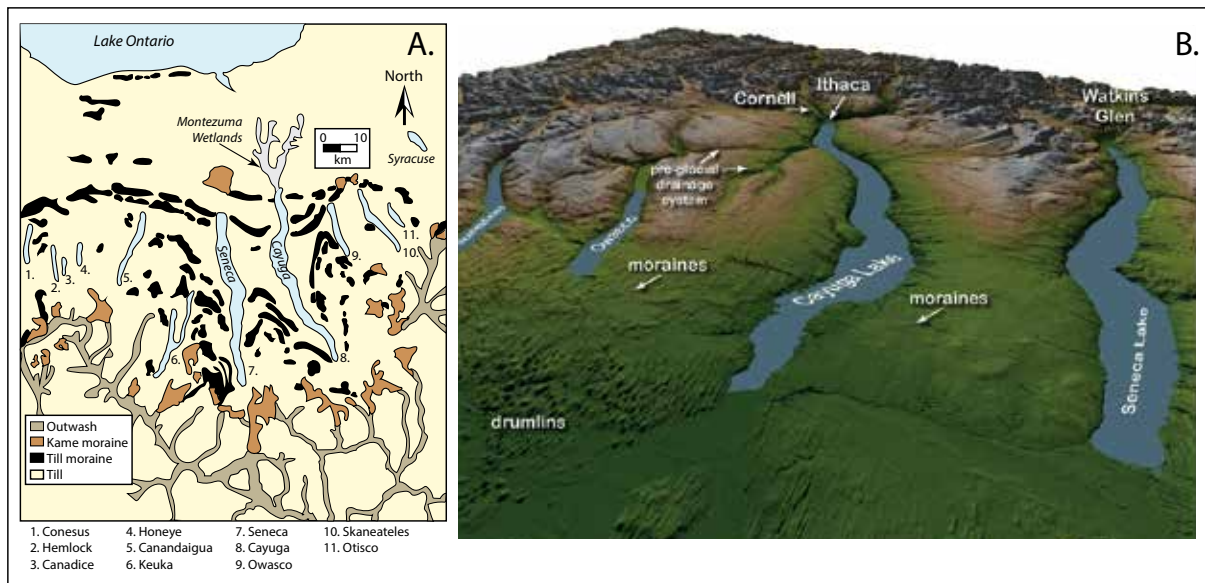


Figure 10. Finger Lakes, upper New York State. A) locality and general surface geology (after Mullins et al., 1996). B) Topography of the Cayuga Lake region looking South and showing the smoothing effects of glacial scour (extracted from images downloadable John Allmendinger's website <[www.geo.cornell.edu/geology/faculty/RWA](http://www.geo.cornell.edu/geology/faculty/RWA)>).

The lakes vary considerably in size, ranging in length from 5 to 61 km, in lake-water elevation from 116 to 334 m, and in maximum water depth from 9 to 186 m (Table 1). Lakes Cayuga (133 m, 435 feet) and Seneca (188 m, 618 feet) are among the deepest lakes in the United States, with bottoms well below current sea level. They are also the longest of the Finger Lakes, though neither width exceeds 5.6 km (3.5 miles); Lake Cayuga is 61 km (38.1 miles) long with a surface area of 172 km<sup>2</sup> (66.4 square miles), while Seneca at 175 km<sup>2</sup> (66.9 square miles) is the largest of the lakes in of water surface area (Table 1).

North of the Finger Lakes, is the Ontario Lowland characterised by an extensive drumlin field and an elaborate system of meltwater channels including Montezuma wetlands north of Cayuga Lake (Figure 10a). The uplands between the Finger Lakes are covered by a thin layer of till with a series of distinct chevron-shaped till moraines (Figure 10b), which become more laterally continuous to the north. The lake valleys are filled with much thicker sequences of valley fill sediments.

Immediately south of the Finger Lake basins, and generally restricted to the valleys, are the <sup>2</sup>kame

moraines (Figure 10a) collectively referred to as the Valley Heads Moraine. Valley Heads kame moraines are thick (locally >200m in the deeper parts of the lake valley fill) and are permeable accumulations of largely coarse-grained, water-lain drift, capable of acting as long-term aquifers (Figure 11).

The original (pre-ice sheet) valleys in the area that is now typified by the various Finger Lakes, likely began as a series of northward-flowing river valleys. This was the geomorphic situation prior to any ice cover, and the alignment of these valleys was probably defined by zones of rock fracture and jointing intensity in the outcropping and subcropping Siluro-Devonian strata.

Southward moving ice sheets have waxed and waned over the original Finger Lake valleys for two million years or more. The main effect of a flowing cover of thick glacial ice is ice-base-scouring and erosion. This makes pre-existing valleys wider, deeper and straighter. Ice is thicker and flows faster over and in pre-existing river valleys, which are preferentially enlarged wherever they are aligned parallel to ice flow. Hence, major valleys of the Finger Lakes region are now aligned parallel with

along the front of a slowly melting or stationary glacier / ice sheet. They are formed by the actions of meltwater streams that flow along the sides of the ice, trapped against it by the valley walls.

2 Kame moraines are mounds of sediment which are deposited

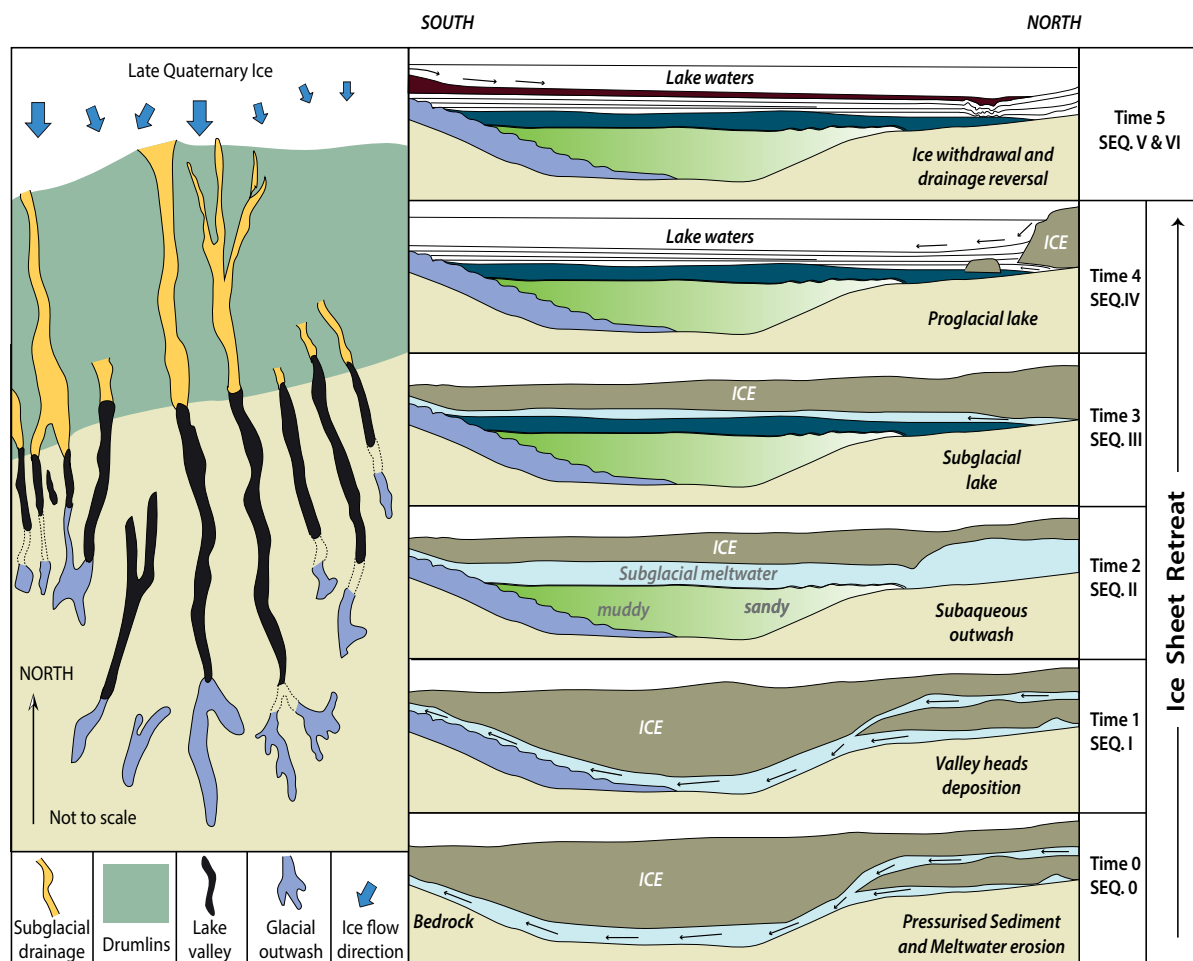


Figure 11. Geological model explaining Finger Lake valley formation as subglacial scour features (after Mullins et al., 1989). At times in the Pleistocene all the lake valleys, including Cayuga Lake, were characterised by an ice overburden that loaded the underlying sediments and so exerted additional hydropressure that abated with the melting and retreat of the ice sheets.

former ice sheets flowing southward from the Lake Ontario area. With episodic ice retreat, the same valleys were filled by various types of glacial sediment. Each southward moving ice sheet over the last two million years largely eroded sedimentary evidence of older glacial deposits in the various valleys and glens.

Glens in the Finger Lakes region are generally aligned at right angles to the principal direction of ice flow and so lay beneath thinner and slower-flowing ice. If the ice was not thick enough it not cover the hilltops and so these regions were not glacially scoured (Figure 10b).

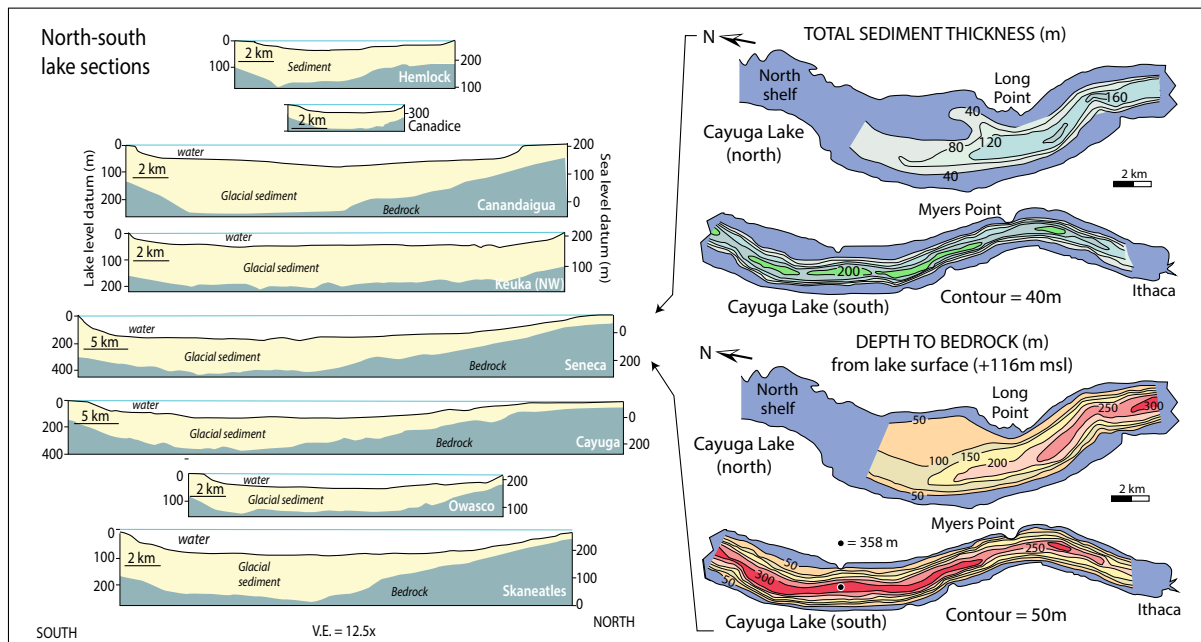
Broad glacial valleys in the Finger Lakes region from which modern streams drain in opposite directions are called through valleys. They occur in the Finger Lakes region (Figure 10a) and are also found in many areas across the Appalachian Upland. Through valleys indicate significant glacial erosion also occurred to the south, east, and west

of the Finger Lakes region and that the Finger Lake region largely preserved the geomorphic features of the last ice advance and retreat (Muller and Calkin, 1993).

Glacially-driven sub-ice-base erosion was most intense beneath Seneca and Cayuga lakes, where maximum depths to bedrock are 300 m and 250 or more metres below sea level, respectively (Figure 12). The ice-retreat model currently used to explain the formation and filling of the various Finger Lakes is illustrated in Figure 11 (Mullins et al., 1989, 1996).

Almost all of the glacial deposits found at the land surface of New York State today were laid down during the Wisconsin stage. During this time the Laurentide ice sheet eroded older glacial deposits, except a few sheltered sites or places that lay beyond the limit of Wisconsin glaciation. The Laurentide ice sheet advanced into western and central New York State around 40,000-35,000 years





**Figure 12. Section and map views of sediment fill statistics of the Finger Lakes, New York State (after Mullins et al., 1995) A) Total thickness of the glacial sediment fill in the various Finger Lakes. B) Total thickness isopach of glacial sediment fill (m) and depth to bedrock isoclinal relative to lake water surface (based on Mullins et al., 1996 seismic interpretation, this has been refined by current interpretation detailed earlier in this report).**

ago during the middle Wisconsinan. The ice margin retreated in western New York State and may be elsewhere before re-advancing some 24,000 years ago during the late Wisconsinan. The maximum stand (ice extent) occurred about 22,000 years ago when the southern limit of ice extended south-east from Salamanca, through northern Pennsylvania and New Jersey, to reach the Atlantic Ocean at Long Island.

Retreat from the late Wisconsinan glacial maximum was underway by 19,000 years ago. Ice may have withdrawn into the Erie-Ontario Lowland before readvancing to the Valley Heads Moraine about 14,000 years ago (Figure 10a). This major moraine marks the southern end of the Finger Lakes valleys and forms the drainage divide between the Chesapeake and the St. Lawrence watersheds. Meltwater drainage was focused into the Allegheny, Susquehanna, and Hudson Rivers.

As retreat continued after 14,000 years ago, proglacial lakes developed in north-draining valleys where water was trapped at and below the melting edge of the ice margin. These lakes in western, central, and northern New York State expanded and merged as the ice margin withdrew northward. Water levels sequentially dropped as successively lower outlet channels emerged from under the retreating ice.

As well as in the Finger Lakes area, proglacial lakes also developed in the Mohawk Valley between the Ontario ice lobe and the Hudson ice lobe, and in the Hudson and Champlain Valleys. The last of these proglacial lakes drained as the Laurentide ice sheet withdrew north of the Adirondack Upland about 12,000 years ago (Muller and Calkin, 1993; Pair and Rodrigues, 1993).

Before we get into a discussion of ice load induced groundwater pumping and fracturing near the edges of continental ice sheets, it is worth remembering that an expanding ice sheet erodes almost all evidence of prior ice sheet events. Worldwide studies of Quaternary sediments in the deep sea show there have been something like 15 or more glacial events in the last 2 million years. The now outdated notion of four glacial events in the Quaternary came from continental glacial sediment studies in North America and Europe. This work was conducted primarily at the edges of former ice sheets where evidence of multiple ice expansion events had been removed by the to and fro of younger ice sheets.

It is highly likely the Finger Lakes region was subject to multiple older ice sheet cover and loading events. But, the evidence on the land surface was removed by the passage of younger ice sheets. We can only study in detail the last (Laurentide) event,

but ice loading with associated pressure pumping has occurred multiple times in the Finger Lakes region in the past 2 million years.

### *Ice sheet loading, flexure and pressure pumping*

The great weight of the Laurentide ice sheet, and earlier ice sheet covers, pushed down the land mass beneath, with the intensity of glacio-isostatic depression greatest in Laurentide time in northern New York State, where the ice was thickest. Immediately following ice retreat (deglaciation), ice loading had caused downward flexure of hundreds of feet in northern New York State (Figure 13). Marine waters entered and flooded the still-depressed St. Lawrence- Champlain Lowland to elevations as much as 325 feet (160 m) above modern sea level. This Champlain Sea lasted for about 1,700 years and gradually drained and retreated eastwards as postglacial rebound raised the area back above sea level (Pair and Rodrigues, 1993).

Worldwide, lithosphere flexuring created by alter-

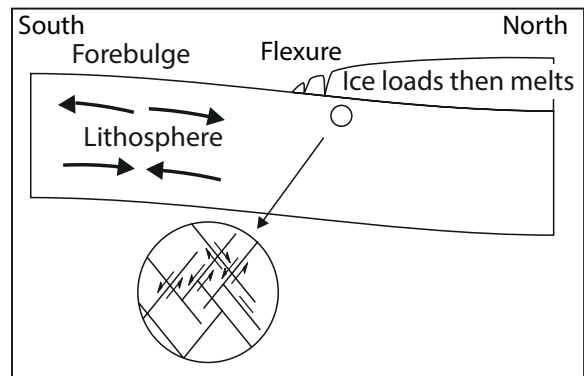


Figure 13. Schematic illustration of how waxing and waning of an ice sheet edge induces fracturing and meltwater or seawater entry into rocks below.

nating episodes of ice-loading and ice retreat drives groundwater entries into underlying beds, especially in the vicinity of ice sheet edges where flexure is greatest (Figures 13, 14; Starinsky and Katz, 2003; McIntosh et al., 2012; Person et al., 2012). Groundwater/meltwater penetration is best documented in former ice edges covering hard-rock (granite and granodiorite) terrains in the cratonic

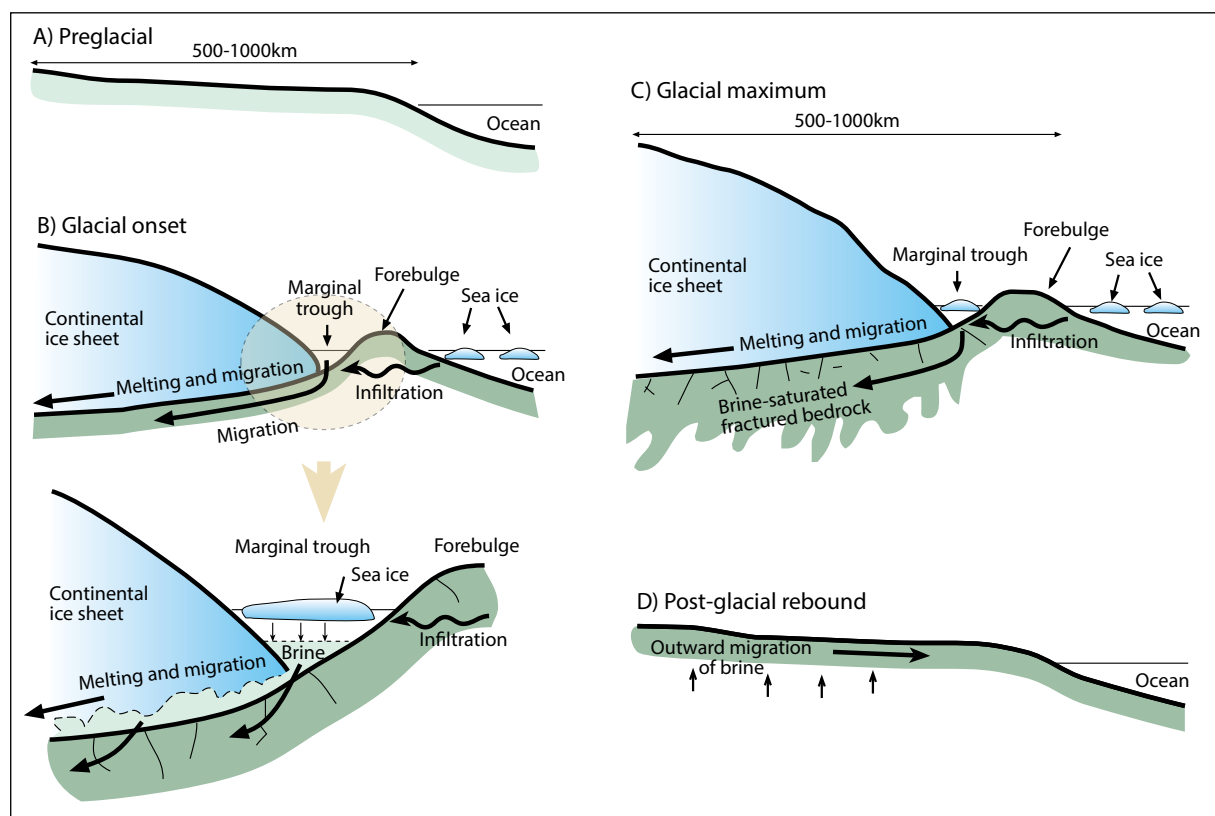


Figure 14. Isostatic and hydrological evolution of a marine-cryogenic-edge basin aquifer system: A) Continent-ocean boundary before the onset of a glacial cycle. B) An ice sheet develops on the continent, depressing the crust underneath and forming a forebulge along the coast. Seawater infiltrates into the marginal trough between the ice edge and the forebulge and sea ice crystallizes on its surface. The resultant brine sinks to the bottom and infiltrates the underlying sediments and rocks via cracks and shear zones and by non-equilibrium melting of the ice sheet base. Then, it migrates inland, along the inclined ice-rock contact, towards the center of the depression. Loss of brine from the trench is compensated by fresh seawater flow through the forebulge. C) During the glacial maximum the basement rocks below the ice sheet become saturated with brine. D) Increased melt water head developing during glacial decline, accompanied by postglacial lithospheric rebound, drive the brines outwards from the center of the glaciostatic depression to their present sites (after Starinsky and Katz, 2003).

shield regions of North America, Europe, Greenland and Antarctica (Person et al., 2012). Many of these places lack evaporites in the subsurface, so the science is more easily documented in their hydrochemistry, compared to upper New York State. There the hydrology is further complicated by ice sheet loading and release, driving long-term brine release tied to ongoing deep salt dissolution. But this dissolution was also occurring well before the influence of waxing and waning glaciers (Goodman et al., 2011; Warren 2016a- Chapter 7).

Ice sheet flexure zones in Antarctica and the Canadian Shield drive seawater-derived brines into the craton to depths of up to a kilometre (Figure 13; Starinsky and Katz, 2003). This flexuring opens joints and fractures and so allows fluid entry into hard rock cratonic areas that would otherwise be impermeable (Figure 14). Even in regions of homogenous hardrock substrate, there are quantified depths fracturing and pressurised water entry measured in several hundreds of metres (Figure 15).

This is occurring in areas without the complication of talwegs cutting deep into evaporitic substrates. However, in some of the deeper examples of water penetration, the dissolution of evaporites creates a fractured and prepared ground of more perme-

able intervals and this has facilitated even greater depths of groundwater penetration (Figure 15).

The Kame moraines tell us the Finger Lakes region was an area of Laurentide ice-sheet edge and edge-induced lithospheric flexuring. As it was in the adjacent Michigan and Appalachian Basins, in the Finger Lakes region the intensity of flexuring was a response to varying ice-weight, along with mechanical contrasts in the substrate related to varying Pleistocene sediment thicknesses in and between the various Finger Lakes. Fluctuating ice load, along with associated downcutting, likely activated and reactivated pre-existing fracture and joint systems in the Siluro-Devonian rocks below the waxing and waning ice sheets.

Contrasts and the propensity for ice-weight induced fracture penetration would have been greater along the edges of the various Finger Lakes, possibly emphasised by steep valley sides and sharp lateral thickness changes in the Quaternary sediment fill.

The effects of ice sheet loading enhancing of salt bed dissolution are active along the northern end of Lake Cayuga and help explains the complete disappearance of shallower salt beds in the northern part of the subsurface geology beneath Lake Cayuga (Goodman et al., 2011).

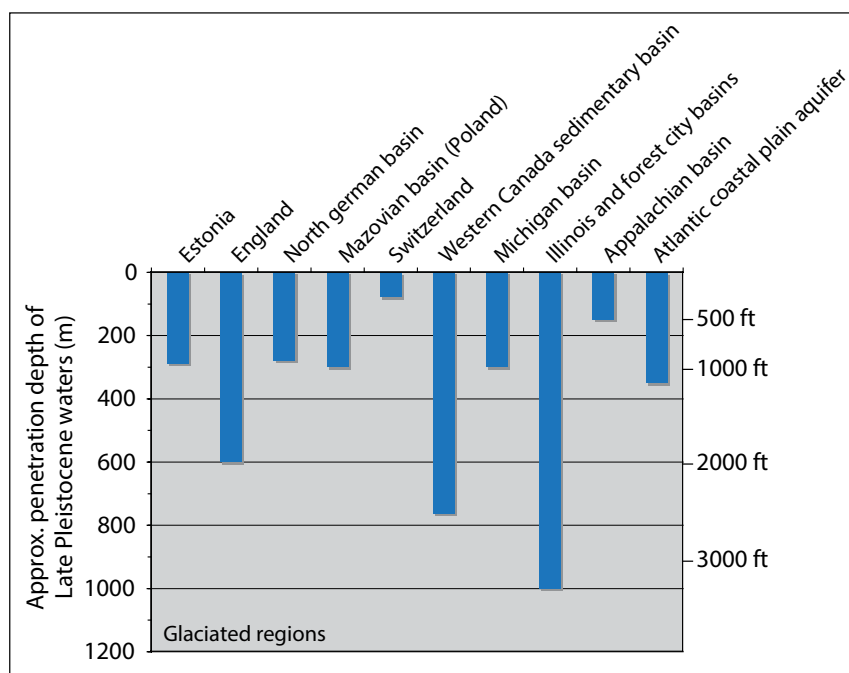
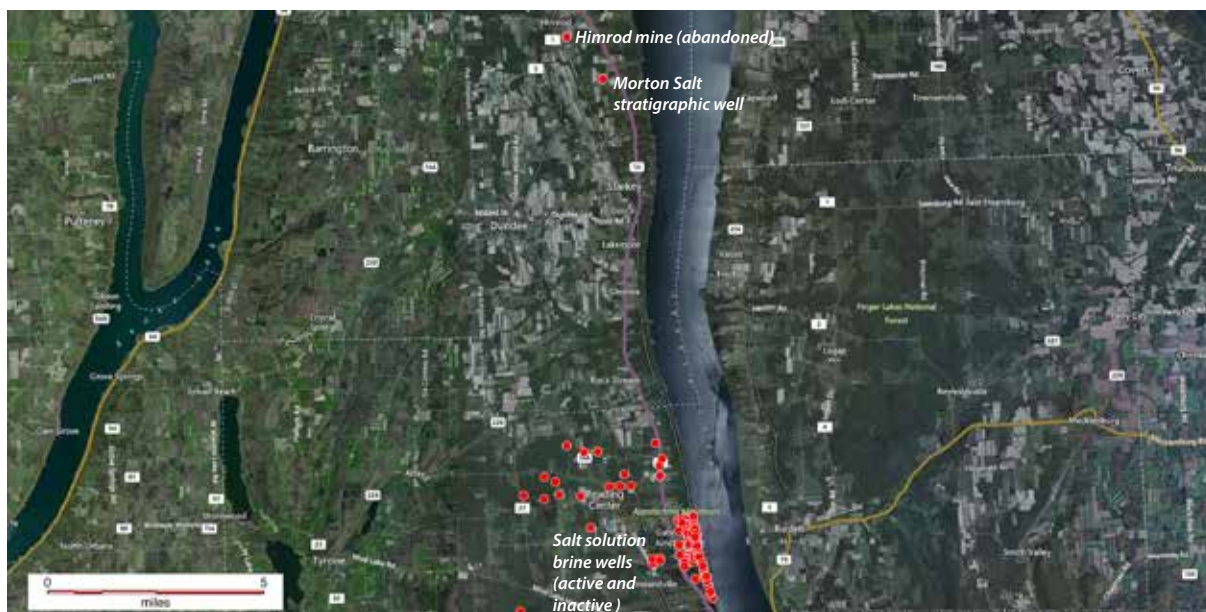


Figure 15. Reported approximate maximum penetration depths of Late Pleistocene meteoric waters in sedimentary basins across North America and Europe (from Person et al., 2012).

Over the last decade, the ability of ice sheet waxing and waning to drive groundwater entry has been quantitatively documented in a number of regions. Figure 15 plots known depths of Late Pleistocene meltwater entry in various regions worldwide (Person et al., 2012) Depths range from 50 m (Switzerland) to a kilometre (Illinois and Forest City Basin), with penetration of a little over 300 m in the Michigan Basin and 150 m in the Appalachian basins. These latter two basins sandwich the study area, so we can





**Figure 16.** Location of the former Morton-Himrod Mine, the Morton Salt stratigraphic well, and various brine field wells to the south.

assume ice sheet flexure was capable of driving groundwater penetration between 150 and 300m ( $\approx 500$ -1000ft) below the base of the ice sheets in the Lake Cayuga (Finger Lakes) region.

Seismic-controlled depth profiles illustrated in Figures 4 and 5 show that in places on the Cayuga Valley floor, the base of the ice that scoured the valley was separated from the Evaporite Section by vertical distances of 300ft and 80 ft, respectively. This means that ice sheet flexuring has likely induced fracturing and jointing in intrasalt carbonate beds below the parts of Lake Cayuga where the downcut into the carbonate section is greatest as indicated by the deepest part thalweg (outlined by the blue line in Figures 2 and 6).

Questions to be quantified before the mining of zones under the lake where the glacial valley thalweg cuts through the Carbonate Beam, and before expanding mine operations northward where the targeted salt layers shallow, are:

- 1) How far south below Lake Cayuga does the influence of meltwater penetration extend into the Syracuse Formation?
- 2) What are the effects of glacial meltwater penetration in terms of roof stability and ore quality?

### **Salt textures in Himrod Mine Core indicative of roof instability**

This section of the report illustrates the utility of a detailed textural study of a salt core as a direct in-

dicator of salt alteration and stability, which in the Finger Lakes region is likely related to ice flexure induced groundwater penetration. Unfortunately, the core from borehole 18, where this work should be done, does not seem to have been studied using these techniques. Instead, we shall apply these textural techniques to a salt core that is in the public domain. This core is from an archived stratigraphic well drill to test the geology of the now abandoned Himrod Mine area (Figure 16). This well was drilled more than 30 years ago, when our understanding of the significance of geological textures in salt was less developed (Warren, 2016a). If the techniques were applied to the Himrod core at the time, it was drilled it is unlikely a geological recommendation would have been made to proceed at that site with what was a very unprofitable mining venture.

It is highly recommended that a textural study is undertaken on the recovered cores in Borehole 18, before Cargill is allowed to continue mining northward, or mine beneath zones below the deeper part of the glacial valley that underlies Lake Cayuga. This study should focus on salt textures in core collected through the Evaporite Interval. Borehole 18 is located on the western shore of Cayuga Lake and lies due west of Cargill's current mining face under Lake Cayuga. It was drilled at the proposed site of Cargill Mine Shaft #4. To date, such a textural study of the core has not been done.

### *The Himrod Mine operation history*

The now abandoned Himrod mine is situated about 1.5 miles west of the Lake Seneca shoreline. The mine was constructed in the 1960s and early 70s, near the town of Himrod, to supply rocksalt to the Morton Salt Plant (Figure 16). The deepest part of the Morton Salt Himrod Mine is approximately 2050 feet (625 meters) deep. Entrance to the mine was gained through two 18-foot concrete-lined shafts equipped with Koepe Hoists (Jacoby, 1977).

The mine was completed and put into operation in 1972 at a cost of \$37,000,000 and closed in 1976. By October 1974, the mine workings covered an area of approximately 1.3 square kilometres. Mining at Himrod was conducted in a down-dip direction to the west-southwest at depths of around 2000 ft in a unit interpreted at the time as the F salt of the Syracuse Formation.

The extraction ratio when operational was around 50 percent (Goodman et al., 2009). With a pre-mining total projected capacity of about 3,000,000 tons annually, the maximum production that was achieved during the mine's short operational life was about 1,200,000 tons. Of the total tonnage produced, 1,000,000 tons were nonmarketable fines, termed F. C. salt, which was typified by a particulate matter size smaller than ten-mesh, with a consistently high level of insolubles, making the product unsuitable for road de-icing.

In June 1974, a miner was killed by a rock fall (Dumas, 1980). In July 1974, two miners were injured in an explosion. In September 1974, 120 workers went on strike. During September 1974, an earthen lagoon wall collapsed, spilling approximately 11,400,000 litres of saline water into Seneca Lake. In addition to subsurface operational and ore quality problems, airborne dust and saline water runoff from the plant were alleged by local residents to have killed trees, lowered yields from farm fields, and created spawning problems for rainbow trout in a local creek (Dumas, 1980; Thompson, 2007).

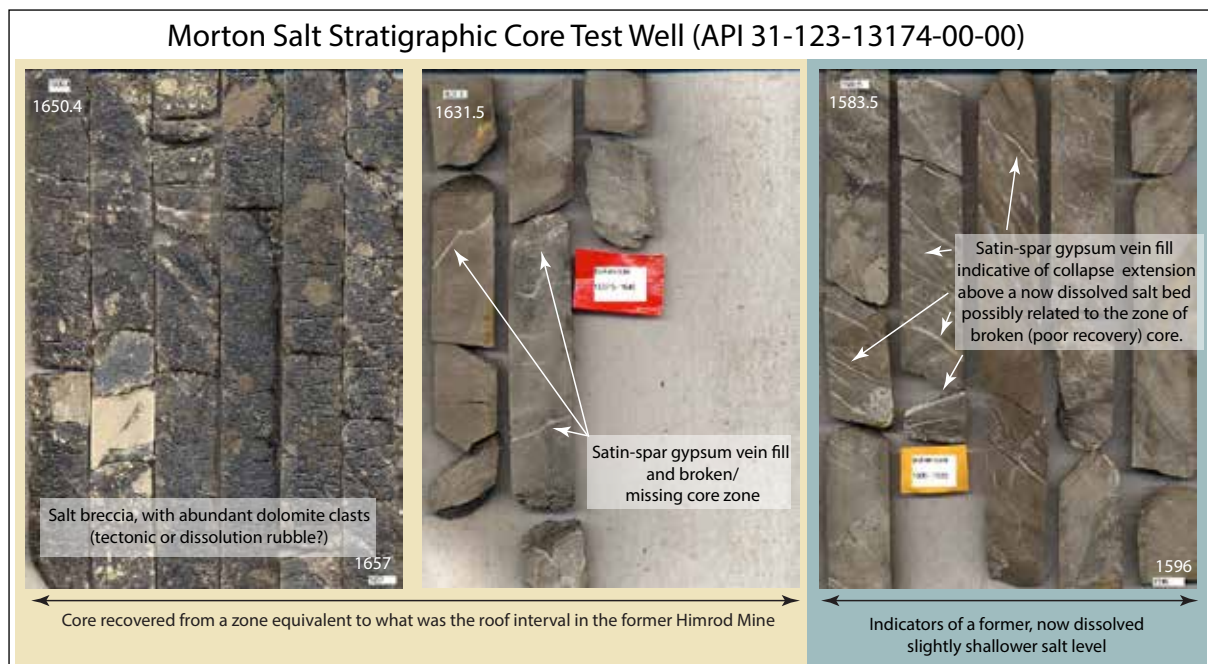
The mine was closed in the late summer of 1976 due to high mining costs, related to a combination of mine roof maintenance costs and high volumes of product with unacceptably high insoluble contents.

### *Salt textures in the Himrod Mine roof*

As part of the Himrod mine setup, a series of cored boreholes were drilled through the main salt layers to define the nature and extent of salt in the vicinity of the mine. Chute (1972) studied these cores and stated, "...These cores provide new information on the stratigraphy and disclose the presence of a flat décollement in the upper part of the Syracuse Formation (Late Silurian)..." Chute (1972) further reported core-based evidence of the collapse of overlying beds, following irregular solution of the salt. He argued this was the cause for some folds in the overlying strata. He also suggested that the décollement horizon may be equivalent to that reported by Prucha (1968) in and around the Cayuga Mine.

What is significant is that Prucha's observations on the nature of the salt is that his main observations come from "within the salt," while Chute's and Jacoby's observations at Himrod used drill core. Coring at Himrod allowed direct observations of the upper contact of the salt, a situation that the ongoing mine operations at Cayuga salt mine try hard to minimise ("stay in the salt" to maximise safety). The Himrod cores directly sample the transition out of the salt into the overlying rocks and so are directly relevant to interpretations of roof stability and any influence of undersaturated water penetration in all mines across the region, including Cargill-Cayuga.

The stratigraphic well at Himrod is the Morton Salt Stratigraphic Core Test well (API 31-123-13174-00-00) and reasonable quality images of the various core trays are still available online (<[http://esogis.nysm.nysed.gov/Cores\\_TOC.cfm](http://esogis.nysm.nysed.gov/Cores_TOC.cfm)>). Selected images of the various Salina Group salt units (B through D) intersected in this well are illustrated in Figure 8 and 9 in Warren, 2016b. Based on the author's experience, all salt textures in these cores indicate that, in addition to some dissolution-induced collapse, salt in the vicinity of the Morton-Himrod Mine had earlier flowed and deformed. The salt layers now constitute a sequence of coarsely recrystallised, structurally-aligned halite layers. The layers had variable thicknesses and degrees of aquifer-induced dissolution, with dissolution effects especially evident in the upper parts of the salt interval (Figures 17).



**Figure 17. Rock-core based observations relevant to the nature of the top of a salt unit and indications of former, now dissolved salt levels in the Cayugan salt of the Salina Group. (Images downloaded from <[http://esogis.nysm.nysed.gov/Cores\\_TOC.cfm](http://esogis.nysm.nysed.gov/Cores_TOC.cfm)>, last accessed Dec.,2016). Refer to Warren 2016b for more detail of other salt textures in this core**

Likewise, the intrasalt beds in this well show evidence of widespread tectonic brecciation and fracturing prior to undersaturated water entry. That is, almost all the textures and structures seen in the salt layer cores, recovered in the Morton Salt Stratigraphic Core Test well, are structural, not depositional (Figure 8 in Warren 2016b). There are no primary layers thicknesses or internal primary sedimentary structures preserved. The salt and its intrabeds are folded and fractured throughout all salt intervals in this well. A lack of a preserved pristine depositional salt stratigraphy is one of the main reasons the Himrod Mine experienced ongoing roof stability and ore-quality problems throughout its short operational life. It indicates a strong likelihood of fracturing and jointing set up by mechanical strength discontinuities during the Appalachian orogeny. These fractures were annealed during subsequent burial diagenesis, but hundreds of millions of years later remained as zones of potential weakness that could facilitate water entry into the Syracuse Formation, especially in areas of glacially induced overburden erosion and thinning.

The exact nature of the roof to the salt in the Himrod area and the presence of dissolved salt layers is indicated by textures in the recovered core (Figure 17). First, there is a zone of poor core re-

covery (rubble in the core above the last zone of recovered core at top salt), which is an indication of a lack of mechanical integrity at this level in the stratigraphy. The last core tray below this rubble zone shows the salt at this level is a highly-disturbed, highly-impure salt breccia. Second, in the horizons above the currently exploited salt layers, there are many layers indicating dissolved salt in the form of evaporite dissolution breccias. These levels are characterised by disturbed and rotated blocks, typically separated by abundant veins of satin-spar gypsum (Figure 17). Satin spar gypsum indicates extension in response to cavity creation, formed as the salt dissolves naturally in zones of undersaturated porewater cross flow. The dissolution creates the void space where the satin-spar vein-fill then precipitates (Warren, 2016b). This set of classic dissolution textures is an indication of an undersaturated hydrology and that Cayugan salt is dissolving, with its products passing naturally into aquifers supplying the regional hydrology.

The importance of the textures in the cores illustrated in Figure 17 is that they show aquifer connection, so assumptions of present-day isolation of the salt from fractured aquifers are not correct. These textures indicate that assumptions of no hydraulic connection between salt and fractured Palaeozoic aquifers that were assumed in the planning stage of the mine were wrong.



### *Problems leading to shutdown and abandonment at the Himrod Mine*

Mining at Himrod was conducted in a room and pillar system, which required the significant close-spaced bolting of the roof. Jacoby (1977) noted many areas of the roof were so unstable as to require bolting through mesh and bars on much closer centres than normal for most salt mines. After extraction of the salt had been completed in an area, large portions of the mine were then closed off as a precautionary safety measure due to roof stability problems. Historically, roof stability has not been a significant problem over most of the southern extent of the Cayuga salt mine, where mined-out rooms were not subject to roof collapse for periods of twenty years or more (Prucha, 1968). However, in the older, now inactive, eastern portion of the Cayuga Mine roof-falls were a problem.

### **Retsof Mine flood and downcutting**

At the time it was operational, the 24 km<sup>2</sup> area of subsurface workings in the AKZO-Retsof salt mine, made it the largest underground salt mine in the USA and the second largest salt mine in the world (Figures 18a). The Retsof mine was lost to water flooding in 1994-1995. Before abandonment, the mine had been in operation since 1885, exploiting the Silurian Salina Salt and before shut down was producing a little over 3 million tons of halite each year. At that time it supplied more than 50% of the total volume of salt used to de-ice roads across the United States.

A complete documentation of the Mine its salt geology and its collapse history are given in Warren 2016b. The next section focuses on the Retsof Geology as it relates to the nature of aquifer connection to the glacial units above the mine roof and how this geological situation was likely to create potential mine roof stability problems.

### *Geology and hydrology of the Genesee Valley in the vicinity of the Retsof Mine collapse*

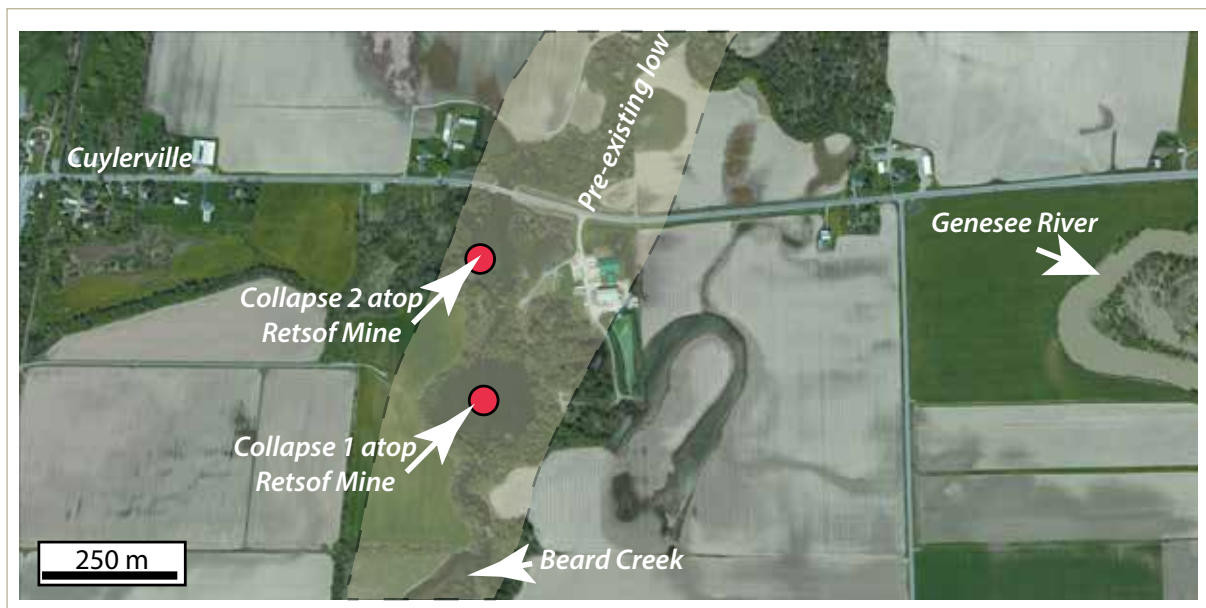
The Genesee Valley sediments preserve evidence of several complex geologic processes that include; (1) tectonic uplift of Palaeozoic sedimentary rocks and subsequent glacio-fluvial down cutting, (2) waxing and waning glacial events that drove erosion of bedrock and the subsequent deposition of as much as 750ft of glacial sediments; and

(3) ongoing erosion and deposition by postglacial streams (Figure 18b; Yager, 2001; Young and Burr, 2006). The Genesee Valley, a glacial scour valley that today spans western New York north to south from Avon, NY to Dansville, NY, including the Canaseraga Creek up through its mergence with Genesee River. A detailed section from Palaeozoic rocks and younger are recorded in outcrop and subcrop in the Genesee River Valley (Figure 18b); however, detailed analysis of glacial sediments and till are still somewhat scarce. The B6 salt bed (Retsof Bed) of the Vernon Formation was the salt unit extracted at the Retsof Mine (Figures 18b). Several other salt layers exist in the Salina Group both above and below the B6. These salt layers include two horizons in Unit D at the base of the Syracuse Formation approximately 50 m (160 feet) above the B6 salt level.

Quaternary-age sediment in the Genesee Valley consists mostly of unconsolidated glacial sediments ranging up to 750 feet thick. These sediments encompass gravel, sand, silt and clays that were deposited mostly during the middle and late Wisconsin deglaciation and filled the lower parts of the pre-existing glacial scour valley. End moraines consisting of glacial debris were deposited in lobes to the south of the slowly retreating glacier (Figure 18b). This geology shows a glacier/ice sheet first scoured through the valley, carving out bedrock and later accumulating sediment during ice sheet retreat. After steep-sided valley walls were cut, the glacier and the associated ice sheet edge periodically retreated as pro-glacial lakes formed in front of the melting ice. Glacial lake sediments are dominated by muds, but also include large boulders and cobbles carried to the lake depressions by ice flows. Fluvial sediment from the Genesee River and Canaseraga Creek also drained into these glacial lakes.

At Retsof, a final pro-glacial lake formed as the Fowlerville end moraine was deposited. The Fowlerville end moraine extends approximately 4.5 to 8 miles north of the Retsof collapse site (Section B-B' in Figure 18a). The various glacial lakes and moraines disrupted the normal flow fluvial patterns of most local drainages and creeks in the valley. Alluvium is the uppermost layer beneath the modern landsurface and is variable in thickness throughout the valley, but normally ranges around





**Figure 19.** Location of the collapse dolines atop the former Retsof Mine to the east of the town of Cuylerville. The doline occupies a pre-existing low that had also captured Beard Creek (Bing® 2012 image mounted and scaled in MapInfo).

fifty feet thick and is still being deposited across the Genesee River Valley floodplain (Yager et al., 2001).

Most significantly in terms of our discussion, the various moraines in the vicinity of the former Retsof mine define ice sheet edges and so indicate a zone of ice sheet flexure and likely groundwater/meltwater penetration into the Syracuse Fm, especially in zones characterised by thinning of the overlying Carbonate Beam.

The modern aquifer system is hosted within the glacial valley-fill and consists of three main aquifers separated by two confining layers. It is underlain by water-bearing zones in fractured Palaeozoic bedrock (Yager, 2001). The glacial aquifers are bounded laterally by the glacially-scoured bedrock valley walls. The uppermost aquifer consists of alluvial sediments 20 to 60 ft thick (unit 1 in Figure 18b); the middle aquifer consists of glaciofluvial sand and gravel less than 10 ft thick (unit 3 in Figure 18b); and the lower aquifer consists of glaciofluvial sand and gravel about 25 ft thick overlying the bedrock valley floor (unit 5 in Figure 18b). These aquifers are separated by aquitards dominated by muds and clays (Units 2 and 4 in Figure 18b).

The now abandoned Retsof Mine lies 550 to 600 ft below the glacially eroded base of the Genesee Valley floor (Figure 18b). Hence, the upper and middle glacial aquifers are separated by an upper

confining layer of lacustrine sediments and till as much as 250 ft thick, and the two confined aquifers are separated by a lower confining layer of undifferentiated glaciolacustrine sediments as much as 250 ft thick.

This modern aquifer system resides in sediment deposited in the Late Pleistocene above and older than the glacially scoured valley floor. It is likely that various older ice sheets that scoured the valley were responsible for earlier episodes of ice-flexure induced groundwater penetration. But sedimentary evidence of these older ice sheets has been eroded by the scouring action of the youngest ice sheets in the region. In the modern aquifer system, we only see the Pleistocene sediment fill from the last episode(s) of glacial melting.

The principal water-bearing zone in the bedrock below the glacial valley floor and overlying the former mine consists of fractured carbonates and sands, with the most permeable interval located near the contact between the Onondaga and Bertie Limestones. The fractured aquifer that occurs at this level in the stratigraphy is have thought to have supplied a significant volume of the water that ultimately flooded the Retsof Mine (Figure 20). The glacial aquifers are hydraulically connected at the edges of the confining layers and in subcrop zones in the present-day valley base, where water-bearing zones in the bedrock intersect a fractured and karstified bedrock surface.

Ground water within the valley generally flowed northward and updip before the mine collapse (Yager et al., 2001). The hydraulic head distribution in the confined aquifers under natural (before the mine collapse) conditions is assumed to have been similar to that in the upper aquifer before the collapse, but water levels in the confined aquifers were probably above the water table beneath the valley floor. Much of the ground water reservoir along the fractured Onondaga/Bertie Limestone contact also flowed northward to escape at the Bertie Limestone subcrop, now located in the valley north of the Fowlerville Moraine (Figure 18).

#### *Events indicating the loss of mine roof stability*

The eventual loss of the Retsof Salt Mine occurred in stages, driven first by “out of salt” roof breaches, followed by ongoing salt dissolution of the water-encased salt pillars in the flooded mine (see Warren 2016b for a detailed history and discussion in possible focus to the flood breach induced by changes in pillar spacing). Mine flooding and land-surface collapse began in the early morning hours of March 12, 1994, with a magnitude 3.6 earthquake. The quake was caused by the catastrophic breakdown of a small mine pillar and panel section some 340 meters below the surface and was accompanied by the surface collapse of an area atop the mine that was some 180 by 180 meters across and 10 meters deep (Figure 19a). This all occurred at the southern end of the mine near the town of Cuylerville. A month later, on April 18, an adjacent mine room collapsed to form a second collapse crater (Figure 19). The initial March 12 collapse in the mine was accompanied by an inrush of brine and gas (methane) and by a sustained intense inflow of water at rates in excess of 70 m<sup>3</sup>/min, via the overlying now fractured limestone back (Gowan and Trader, 2000).

In a little more than a month, the two steep-sided circular collapse features, some 100 meters apart, had indented the landscape above the two collapsed mine rooms (Figure 19). The northernmost collapse feature, which was more than 200 meters across, included a central area that was about 60 meters wide and had subsided about 6 to 10 meters. The southernmost feature, which was about 270 meters in diameter, included a central area that was about 200 meters wide and had subsided about 20 meters (Figure 19). Fractures extending

up from the broken mine back created hydraulic connections between aquifers, which previously had been isolated from each and so provided new high volume flow routes for rapid migration of perched groundwaters into the mine level.

Water flooded the mine at rates that eventually exceeded 60,000 litres per minute and could not be controlled by pumping or in-mine grouting. By January 1996 the entire mine was flooded. Associated aquifer drawdown caused inadequate water supply to some local wells in the months following the collapse; the fall in the water table as ground waters drained into the mine in effect meant some water wells went dry (Figure 20; Tepper et al., 1997).

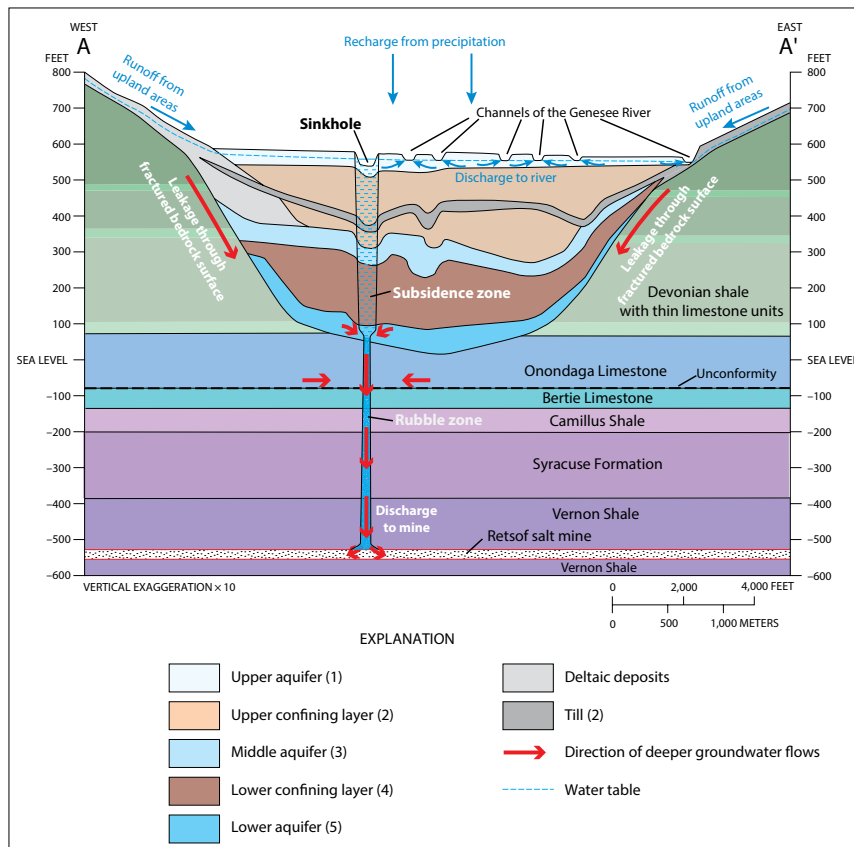
Aside from the loss of the mine and its effect on the local economy, other immediate adverse effects included abandonment of four homes, damage to other homes (some as much as 1.5 kilometers from the sinkholes), the loss of a major highway and bridge, loss of water wells and prohibition of public access to the collapse area (Figure 19). Land subsidence, possibly related to compaction induced by aquifer drainage to the mine, even occurred near the town of Mt. Morris some 3 miles south-west of the collapse area. The longer term adverse effects are mostly related to increasing salinization of the lower parts of the Genesee Valley aquifer system in the vicinity of the mine (Yager, 2013).

#### *What caused the loss of the Retsof Mine?*

Post-mortem examination of closure data from the two failed mine panels has been interpreted as indicating an anomalous buildup of fluid pressure above the panels in the period leading up to their collapse (Gowan et al., 1999). The initial influx of brine and gas following the first collapse coincided with the relief of this excess pressure.

Gowan and Trader (1999) argued for the existence of pre-collapse pressurised brine cavities and gas pools above the panels and related them to nineteenth-century solution mining operations. They document widespread natural gas and brine pools within Unit D of the Syracuse Formation approximately 160 ft above the mined horizon in the Retsof Mine. The satellite image also shows that collapse occurred in a pre-existing landscape low that defined the position of Beard Creek valley above





**Figure 20. Stratigraphic section depicting rubble chimney above collapsed room in Retsof salt mine, Livingston County, N.Y. Also shown are the main aquifers that facilitated water influx into the flooding mine (inflow also drained natural and artificial brine-filled solution cavities in the stratigraphic levels above the working mine level (after Yager et al., 2009)**

the mine (Figure 19). Brine accumulations likely formed in natural sinks, long before salt solution mining began in the valley. Salt in the shallow subsurface dissolved naturally, driven by the natural circulation and accumulation of meteoric waters along vertical discontinuities, which connected zones of dissolving salt to overlying fresh water aquifers (see Warren, 2016b, Chapter 7 for a detailed documentation of this salt related hydrology and geomorphology).

Gowan and Trader (2003) argued that daylighting sinkholes had formed by the down-dropping of the bedrock and glacial sediments into pre-existing voids created by the dissolution of salt and the slaking of salt-bearing shale upon exposure to fresh water. It is likely that the extent of these brine filled voids was exacerbated by the “wild-brining” activities of salt solution miners in the 1800’s.

Nieto and Young (1998) argue that the transition to the yield pillar design was a contributing factor to the loss of mine roof integrity. Loss of mechanical integrity in the roof facilitated fracturing

and the influx of water from anthropogenic “wild brine” cavities.

The exact cause of the loss of roof integrity and subsequent mine flooding is still not clear. What is clear is that once the Retsof mine workings passed out of the salt mass, and into the adjacent non-salt strata, the likelihood of mine flooding substantially increased. Even so, the loss of the Retsof salt mine to flooding was a total surprise to the operators (Van Sambeek et al., 2000). The mine had operated for 109 years with relatively minor and manageable incidents of structural instability, water inflow, and gas occurrences. A substantial database of geological information was also collected throughout the his-

tory of the mine. It was this relatively uneventful mine history and the rich technical database that provided support for pre-inflow opinions by mine staff that there was no significant potential for collapse and inundation of the mine. The Retsof collapse took place in a salt-glacial scour stratigraphy and hydrology near identical to that in the Himrod and Cayuga Mine regions.

The two competing notions of the dominant causes for the Retsof roof collapse both accept flooding was initiated by mechanical weakness in the roof above the mine workings. One argues for anthropogenic brine pockets the other for a change in pillar spacing. We think there is an additional factor at work in causing the Retsof roof collapse and flooding. This is glacial downcutting of the valley floor (thalweg) into the carbonate beam and associated ice sheet flexure driving the entry of undersaturated meltwater/groundwater into the Syracuse Fm. This mechanism drove water entry into the Devonian-Silurian succession tens to hundreds of thousands of years in advance of mining

operations. Below the deeper parts of the glacial valley thalweg, where the salt overburden is thinner, it set ups a more deeply penetrating ice sheet flexure hydrology in the Syracuse Formation that created pre-mine fractures, salt dissolution and collapse breccias (with satin spar associations).

In the cross sections shown as Figures 18b and 20, and based on borehole data and generalised seismic interpretation, there are some 500-600 ft (150-180 m) of strata separating the base of the scoured glacial valley and the targeted salt ore. This distance puts all the rock in the zone above the salt ore layer (including the mine roof) in a zone that would have been subject to undersaturated meltwater/groundwater entry (see Figure 15). The alteration of the roof and overlying strata would have created a prepared and altered background geology suitable for collapse as the mine workings approached.

## Conclusions

Integration of public domain seismic from Cayuga Lake with the lake's known geology and cross ties to more regional salt geology, especially that in Himrod and Retsof Mines, gives the following conclusions:

- 1) Glacial downcutting in Lake Cayuga has cut into the Siluro-Devonian seismic unit defined in this report as the "Carbonate Beam."
- 2) Along the resultant thalweg of the glacial valley, as little as 80 feet of geological section remains above the seismic unit termed the "Evaporite Section." This would mean that the carbonate beam has been eroded out and only weaker shales of the Camillus Formation now sit above the evaporite unit. The evaporite unit contains the ore level salt layer currently exploited in the Cayuga Salt Mine, as well as younger salt layers and their remnants above.
- 3) The glacial geology of Lake Cayuga, especially the kame moraines at the southern end of the lake show that at the end of the last glacial the lake was located at the southern edge of the kilometre or more thick Laurentide ice sheet.
- 4) The Laurentide ice sheet is the most recent of a number of ice sheets that periodically covered the Finger Lakes region in the past two million years.
- 5) Differential loading by passage and melting of the Laurentide ice sheet and other earlier ice sheets sets up a tectonic situation called ice-sheet flexure, which deforms and fractures parts of the lithosphere near the ice sheet edge.
- 6) Worldwide, flexure and rebound at the Laurentide ice sheet edge have driven the penetration of undersaturated ice sheet flexure waters (meltwaters and groundwaters) to distances of up to a kilometre below the base of the ice.
- 7) Documented vertical water penetration distances in the nearby Michigan basin are 300 m ( $\approx 1000$  ft) and 150 m ( $\approx 500$  ft) in the Appalachian Basin.
- 8) Evaporite Section strata beneath and adjacent to the glacial valley thalweg of Cayuga Lake have likely experienced ice load fracturing and ice-flexure penetration of these undersaturated waters.
- 9) Penetration by similar ice flexure driven groundwaters likely explain the long-term mechanical weakness zones in the Evaporite Section in the vicinity of the mine workings in the former Himrod and Retsof mines.
- 10) Rock textures in a core in the Evaporite section (as illustrated by the Himrod stratigraphic well) can be used to identify zones of undersaturated water penetration.
- 11) Excavation of mine cavities in such water penetrated and weakened strata creates problems in mine roof stability and degrades the quality of the salt ore.
- 12) Seismic definition of the depth of thalweg downcutting into the carbonate beam and ice-flexure water penetration, with associated alteration and dissolution of the Evaporite Section, explains the positions of known salt anomalies in the vicinity of the current workings of the Lake Cayuga Salt Mine.
- 13) Seismic analysis of the public domain data from Lake Cayuga and tentative mapping of the glacial valley thalweg shows; a) stability and mine problems associated with Carbonate Beam downcutting into the Evaporite section and, b) associated ice-flexure driven penetration of undersaturated waters into the Evaporite Section increases north of the current position of the mine workings.

## Recommendations

The NYS Department of Environmental Conservation should consider immediately halting any further exploitation of this thinning bedrock zone until the following have been completed:

- 1) A 3-D seismic survey, or detailed 2-D survey, with acquisition parameters focused on mapping the glacial valley floor and the degree of down-cutting in the Carbonate Beam and the underlying Evaporite Section.
- 2) The same survey should be used to construct a salt anomaly map that defines the position of known and future mine workings with respect to the glacial valley thalweg.
- 3) The salt core at borehole 18 is re-logged using current understandings of the significance of textures and vein structures in salt core, with a view to defining the degree, if any, of ice-flexure driven penetration by undersaturated groundwaters.

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