Technical requirements needed to approve construction of Shaft #4 in the Cayuga Salt Mine, New York State

Authored by

Dr John K. Warren

SaltWork Consultants Pte Ltd (ACN 068 889 127)
Kingston Park, Adelaide, South Australia 5049

www.saltworkconsultants.com

Executive Summary

What drives significant instability at times of salt mine expansion is the unexpected intersection of zones holding substantial halite-undersaturated pore water volumes located in or immediately out-of-salt. Worse yet, is a hydrological connection scenario where the intersected zones possess high potential inflow rates and are connected to large reservoirs of halite-undersaturated pore waters. This is especially so when such unexpected pore waters are connected to the mine workings via open fracture porosity

To date, the New York State authorities have not required of the mine operator appropriate technical data suitable to make a "best-practice" judgement on whether to grant permission to move forward with Shaft #4. Before a firm decision is made, the following set of documentation and studies should be required of the mine operators.

1) What is the geological situation ("stay in the salt") in the areas where an unknown and possibly significant volume of halite-undersaturated water is to be stored? If the proposed water storage area is such that the water volume is fully encased, and it will not weaken the strength of intervening salt pillars, or while stored, drive dissolution and connection with unexpected aquifers in adjacent "out-of -salt" positions, then such below-ground storage of pilot hole and shaft reaming inflows should be feasible.

2. What is the nature of the permeability and porosity in the aquifer level to be encountered at the Bertie -Oriskany levels during upward reaming of Shaft#4. This interval was sampled via cuttings, not core, in Corehole #18 . At this stage, it is not known if the encountered aquifer poroperm is held in a homogeneous medium or held in a highly inhomogenous host, as is typical of a fractured aquifer reservoir. If it is held in a homogenous bedded host, then the pump test already done to quantify entry rates and discussed in the CoreHole 18 report can be extrapolated reasonably well from the narrow borehole diameter to a 14-foot wide shaft. If the aquifer is fractured, then flow rates and aquifer interconnectedness have not been reliably quantified by pump tests in a narrow borehole. Unexpected water volumes may be encountered during upward reaming of Shaft #4.

3. What do the salt textures captured in the core from Corehole #18 indicate in terms of possible aquifer proximity? The current description of salt textures in the RESPEC report does not define the nature of the various processes likely influencing the formation of various salt textures. Current salt sedimentology allows one to differentiate between tectonic, diagenetic and salt dissolution textures and breccias. Work on the publically-available core from the Himrod Mine shows all these textures are present in the salt layers in the Syracuse Fm; they are distinct and capable of being classified. Such a sedimentological study of the salt core in Corehole #18 would better refine the hydrological situation in the vicinity of Corehole #18 and if there is a possible hydrological connection already in existence between the top of salt and the overlying potential aquifers located in and above the Bertie Formation.

The further integration of the salt texture information derived from the core with the mineralogical information already measured in the wireline data run in Corehole #18 would help to refine such a hydrological model, which could then be tied back to the current understanding of the mine geology and improve the utility of predictive ore quality models.

Contents

Introduction 1

Cargill's need to commission Shaft #4 1

Regional Salt Geology 3

Quaternary Geology of the Finger Lakes region of New York State 11

Hydrology of the Cayuga Lake region 11

Saline aquifers and glacial drivers of fluid entry 12

Salt mine problems due unforeseen water entry 15

Retsof Mine, New York State, USA 15

Lake Peigneur, Jefferson Island, Louisiana 18

Patience Lake Potash Mine flood 20

Implications for the Cayuga Salt Mine expansion 21

"Stay in the salt" 21

Conclusions with recommendations 22

References 24

Addendum: How important is is short term humidity variation in terms of mine stability? 26

Introduction

This report stems from a request for technical comments on the general suitability of the salt geology for the proposed sinking of a new shaft using upward reaming on the property of the Cayuga Salt Mine in New York State. Specifically, how would the known geology interact with the safe disposal of the waste and associated stability in existing underground mine workings? The request to SaltWork Consultants Pte Ltd invited Professor John Warren to be the report's author due to his extensive experience in salt studies (www.saltworkconsultants.com). Dr Warren has more than 30 years expertise in all aspects of salt geology, both academic and applied. He has authored four advanced-level books on the topic of salt, as well as numerous papers in internationally-refereed scientific journals.

The report first documents the salt geology of the region, it then documents the Quaternary glacial history of Cayuga Lake and the Finger Lakes region. It focuses on how active deep aquifers currently flow beneath Lake Cayuga and the surrounds. The briny flows evolved in response to loading, driven by the waxing and waning of ice sheets atop the geology southward-dipping Phanerozoic geology of the region. The report then addresses the specifics of this highly saline geological evolution in terms of future mine stability and the storage of waste materials in worked-out regions of the salt mine.

Throughout the reading of this report, the reader should keep in mind that rock salt (which is mostly composed of the mineral halite –NaCl) is a rock type with unusual physical properties. It possesses an extraordinary combination of high solubility in water, low shear strength and yet is largely impervious if left in an unaltered state in the subsurface. This unique combination of properties makes the mining of salt and the long-term stability of abandoned salt mines and solution wells a field of study with many features indigenous to the unusual nature of the exploited salt (See Warren 2016 and Warren, in press; copies of chapters 7 and 13 from Warren 2016 are available in the Endnote® database that accompanies the hi-res pdf version of this report).

The brief for this report is to focus specifically on what information is in the public realm related to the geology of the Salina Group salt and its relevance to decisions of its use as a host lithology. Possible future problems are outlined and discussed in this report only in a general fashion. The matters raised can only be further addressed if specific detailed site geology documentation, currently unavailable to the author, is integrated into any possible future study. Additional relevant aspects of the regional salt geology of the Finger Lakes region are giving in an earlier scoping report (Warren 2015) and in Goodman et al., 2009, 2011, 2015 and in the references therein.

Cargill's need to commission Shaft #4

A new shaft is required for the safe operation of the Cayuga Salt Mine as the current working faces are located almost 4 miles north under the lake from the existing main access shaft (Figure 1). The current access situation is not only problematic regarding escape protocols, but also because the three existing shafts are now showing signs of age and likely water damage, corrosion and longterm salt heave. Having been in continuous operation since 1924 Cayuga salt mine it one of the older salt mines currently operating in the United States. The oldest salt mine in the US is extracting diapiric, not stratiform salt from Avery Island in the US Gulf Coast (Warren, in press).

Cargill Salt is currently seeking permission to construct a new 14-foot diameter access shaft to be known as Shaft #4 (public notification published Sept 9, 2016, in the Ithaca Journal). Located at 1001 Ridge Road (St. Rte. 34B) in the Town of Lansing, Tompkins County, at an elevation ≈890 ft the site has a proposed surface extent of some 12.3 acres and is located some 3.9 miles north of Cargill's current access shafts. The geology at this planned construction site is based on cuttings and core recovered in a stratigraphic well known as Core-hole 18 (RESPEC, 2013). Much of the geological detail in the vicinity of the proposed shaft comes from a reading of this RESPEC report by the author. It is assumed that Shaft #4 will be constructed in the vicinity of Corehole #18 (42.571830N, 76.582346W)

The most likely method of shaft construction being considered by Cargill involves controlled upward stoping, beginning at the level of current subsurface mine workings and is known as raise boring (Liu and

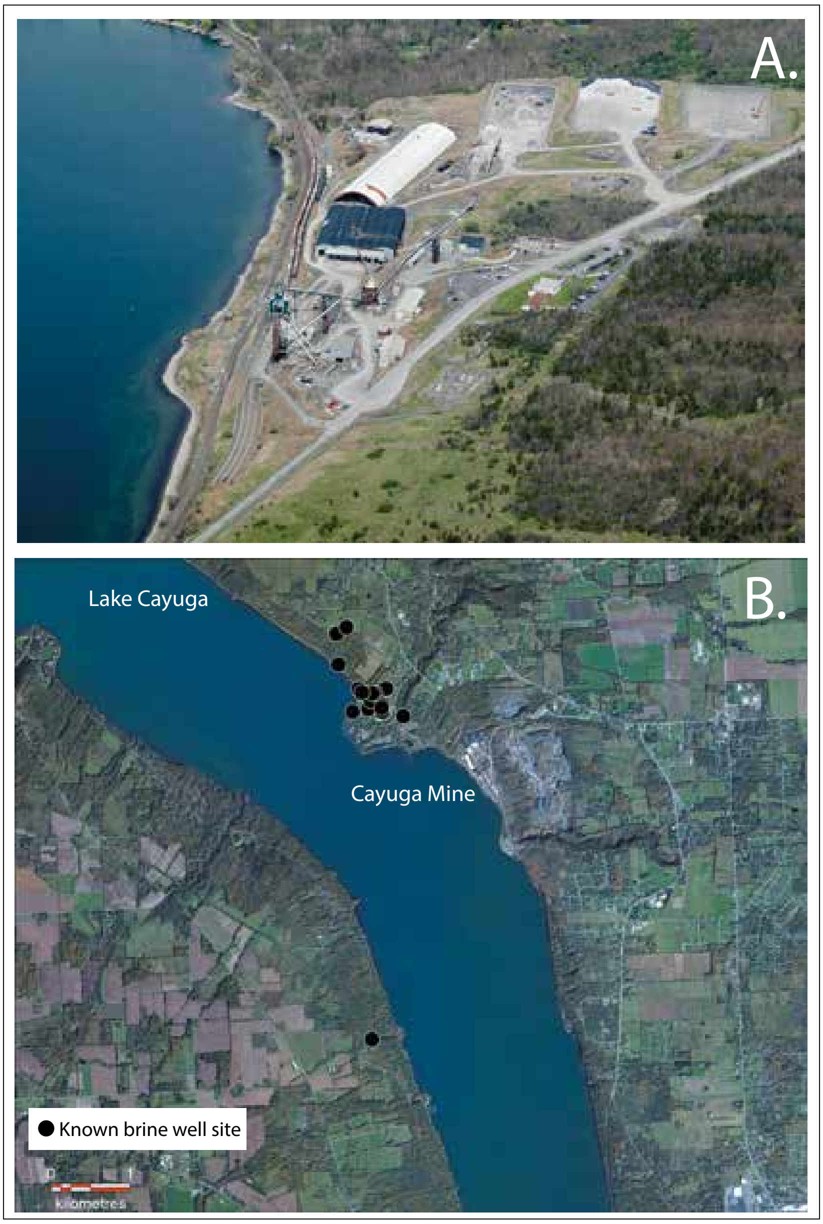

Figure 1. Cayuga Salt mine, New York State. A) Current lake shore position of Cargill Salt's main shaft and surface operations. B) Positions of documented brine wells ranging in age from the 1890s until the 1970s and extending to depths of more than a kilometer.

Meng, 2015). If chosen, this method involves installing an initial 18-inch pilot hole to the mine level, and then attaching the reaming bit, which is then pulled upward to the surface to create the 18-foot opening for the final shaft construction (Figure 2). Both of these holes will be open to the mine level to allow any cuttings and fluids encountered to fall to the mine for removal.

The advantage of this construction method is that all waste and brine can be immediately removed into storage and disposal in mined out portions of the existing workings. The method is cost effective compared to a surface excavation of an access shaft downward, and has an additional advantage of no unsightly wastepile at the surface during construction. It further reduces costs as there is no need to dispose of any brine or other pumped subsurface fluids into surface storage facilities. Rather, any collected brine or brackish water can be moved directly into subsurface storage sumps located within older already worked parts of the mine.

The disadvantage of this construction method is that if the work encounters severe conditions during shaft construction, such as unexpectedly high volumes of water inflow are intersected, or a loss of roof stability occurs, then it is a system that is not easily plugged or isolated. Roof control is not easily recovered without significant sub-roof damage. If the event is associated with high levels of water influx, there is a strong possibility of ultimate loss of existing underground facilities (see Retsof Mine case history). However, Cargill successfully used the same shaft construction method in building existing facilities to the south.

Cargill is proposing to integrate and store any aquifer leakage waters flowing into the shaft during and after construction (likely from intervals in and above the Bertie Formation), for consolidating fines that will be disposed of within regions of already mine dresidual panels. The plan will also utilise this stored groundwater for reduction of dust in active parts of the mine. To dispose of waste/water/brine generated during the construction of Shaft #4, a temporary sump will be constructed to collect pilot hole, construction, and shaft water. This water/brine then will be pumped to the U60 and U58 regions in the current mine for storage. In the proposed plan up to 75 gpm can be pumped and

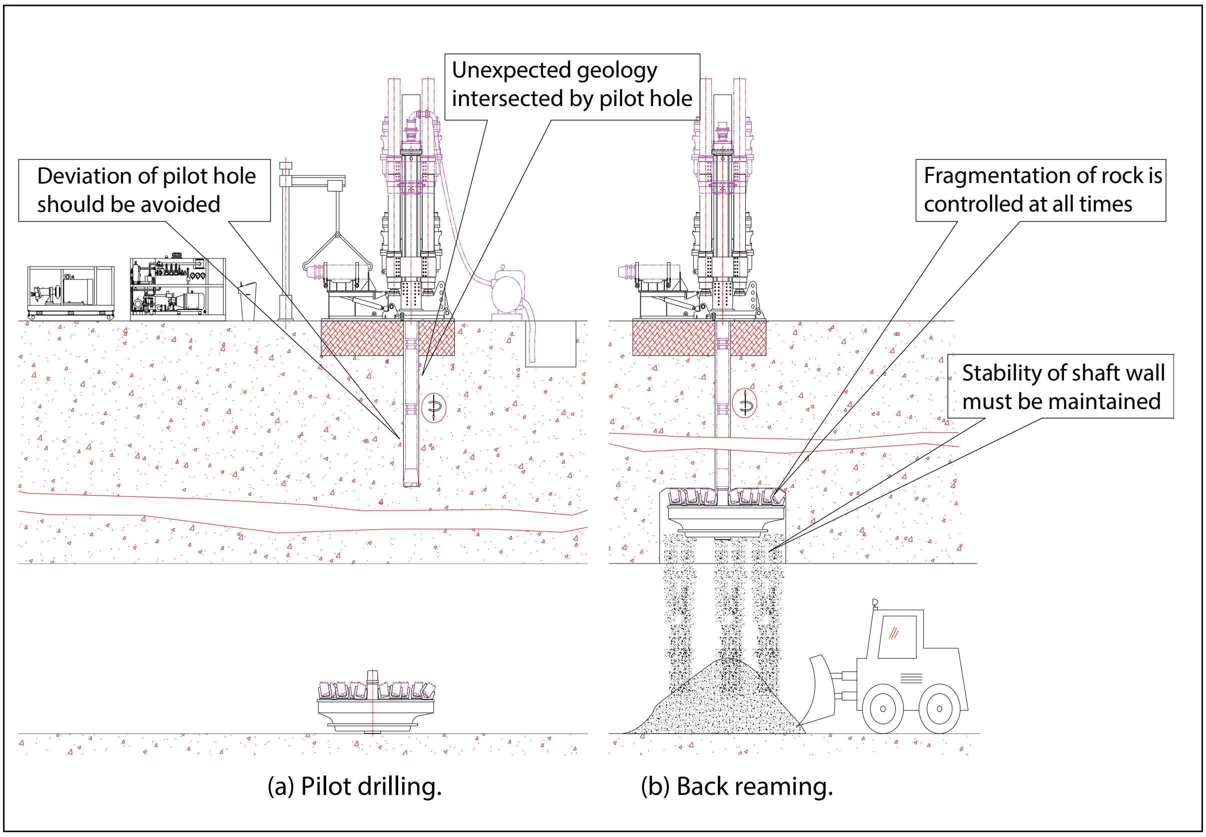

Figure 2. Raise Boring (upward-reaming) method of shaft construction and requirements to maximise stability and control during construction (after Liu and Meng, 2015)

it is expected over the shaft construction period that some 5.5 million gallons will be generated. According to Cargill, regions U58 and U60 can accommodate over 13 million gallons of water without roofing or leakage.

The rate of brine inflow postulated to come mostly from or above the level of the Bertie Dolomite is based on pumping tests conducted after an unexpected aquifer was intersected during the drilling of Corehole #18 (RESPEC, 2013). This level in the stratigraphy is defined by a major regional unconformity (Figure 2). The known salinities of the inflow waters will make the collected water undersaturated with respect to rock salt (halite). Possible effects on roof and pillar stability during the reservoiring of significant volumes of undersaturated water underground are discussed later.

Corehole #18 identified a significant aquifer at approximately 1,490 ft bgs (below ground surface) in the Oriskany Sandstone with a flow rate that was estimated in the field at the time of drilling to be ten gpm (gallons per minute). However, the subsequent pumping test (after two pump failures) suggested that the sustained inflow rate into the borehole was approximately three gpm. Lower in the stratigraphy, in proximity to the mine's current workings beneath the eastern uplands, the base of water can reasonably be expected to be at, or above, the base of the Bertie Group. Gas was observed in the Oriskany Sandstone at 1,505 ft bgs with an estimated production rate of approximately 13,300 cfd.

The proposed final reclamation plan states that when Shaft #4 is decommissioned at some time in the future this will involve removal of any piping or operating systems from the shaft, injecting of a cementitious low-permeability flowable fill (nature of fill not further specified) that will permanently seal the shaft and will also require the filling the uppermost eight to ten feet of the shaft with a high-strength concrete plug. The surface facilities will remain to provide office and commercial facilities for future use. The reviewed additional life-of-mine area is 12.3 acres.

Regional Salt Geology

Salt in the Cayuga Lake region is currently extracted in solid form from the Cayuga salt mine mostly for road de-icing (see Cayuga Salt Mine). The salt source lies in

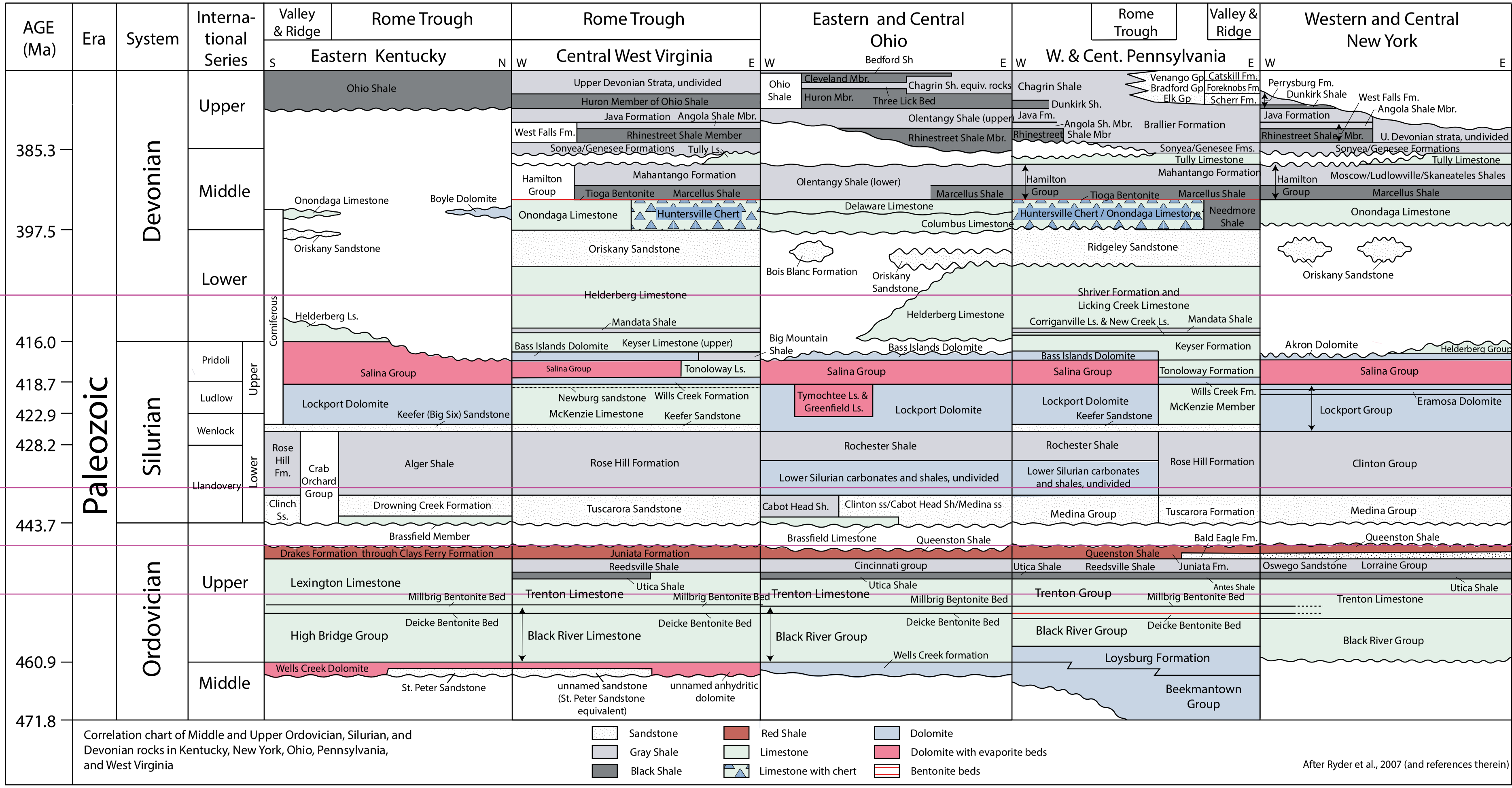

Figure 3. Stratigraphic correlation panel showing how the rock unit names vary across the region, but the evaporitic Salina Group is regionally extensive (extracted from Ryder et al., 2007)

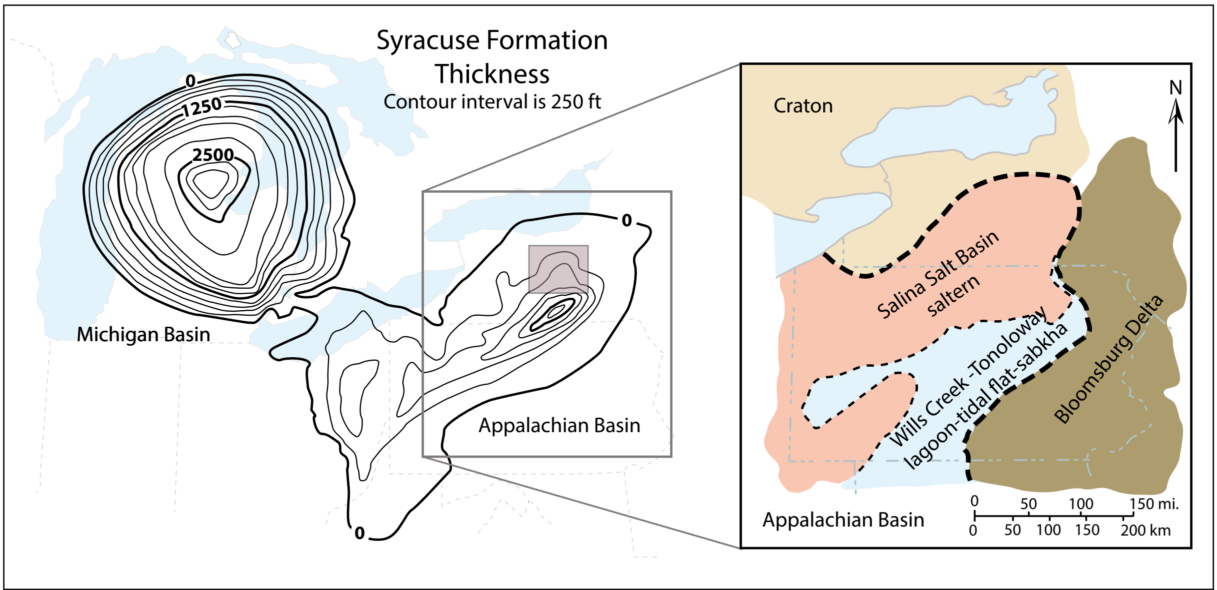

Figure 4, Distribution and thickness of salt in the Salina Group.

variably dissolved and deformed beds of the Vernon and Syracuse formations that together make up the Salina Group. The 416-418 million-year-old (Silurian) Salina Group extends from Michigan through upstate New York and into the Appalachians and south into Indiana (Figures 3, 4).

In the Michigan basin, the Salina Group reaches thickness greater than 2,500 feet (760 m) and consists dominantly of sub-horizontally bedded alternating carbonate rock and salt layers (Figure 3). Southward of the Michigan Basin the Salina Group lacks salts, becomes thinner (both depositionally and erosionally), and extends into a

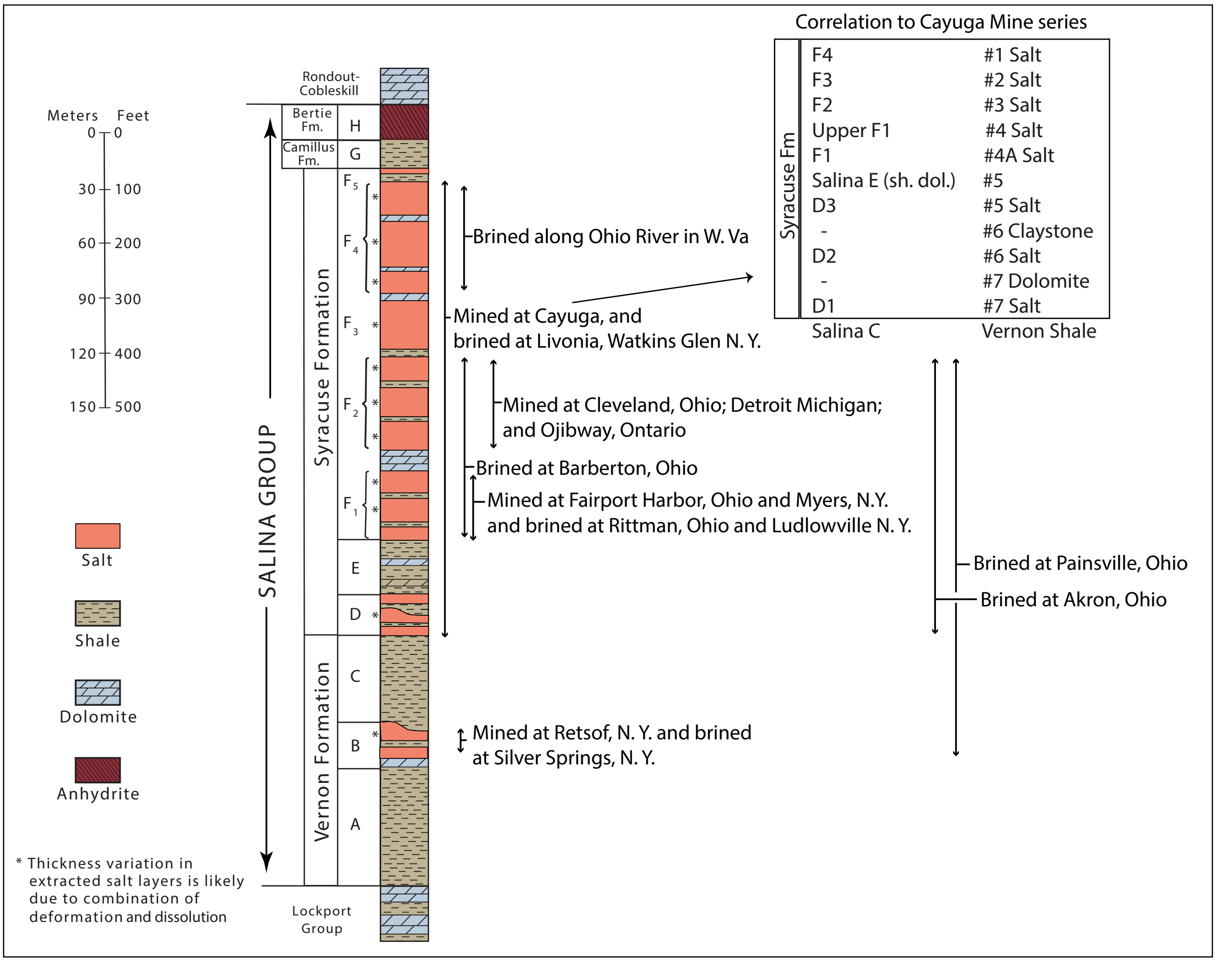

Figure 5. Stratigraphy (rock unit names) used to describe salt units in New York State and surrounds, along with a listing of targeted salt intervals in former and current mining or brine well operations across the region (after Tomastik, 1997) Insert gives the correlation of the regional stratigraphy to units used in the Cayuga Mine.

roughly wedge-shaped unit ranging in thickness from 500 feet (150 m) (northeastern Indiana) to as little as 50 feet (15 m) (central Indiana). To the east of the thick Salina salts in the Michigan basin, the Salina Group transition into the more structurally-deformed Appalachian Basin (Figure 4), it retains its salt units and in total thickness can exceed 1250 ft (380 m), but individual salt unit thicknesses are more variable (Figures 5).

Depth to top of the Salina Group in the Appalachian Basin ranges from 0 along the outcrop in New York and western Ohio to more than 9,000 ft (2,740 m) deep in the center of the Appalachian depositional basin. The top of the Salina Group ranges from about 1,400 ft (430 m) beneath the shore of Lake Erie to more than 10,000 ft (3,050 m) below sea level in the vicinity of Muncy, Lycoming County, PA. The Salina Group ranges in thickness from about 300 ft (90 m) in Erie County to over 2,200 ft (670

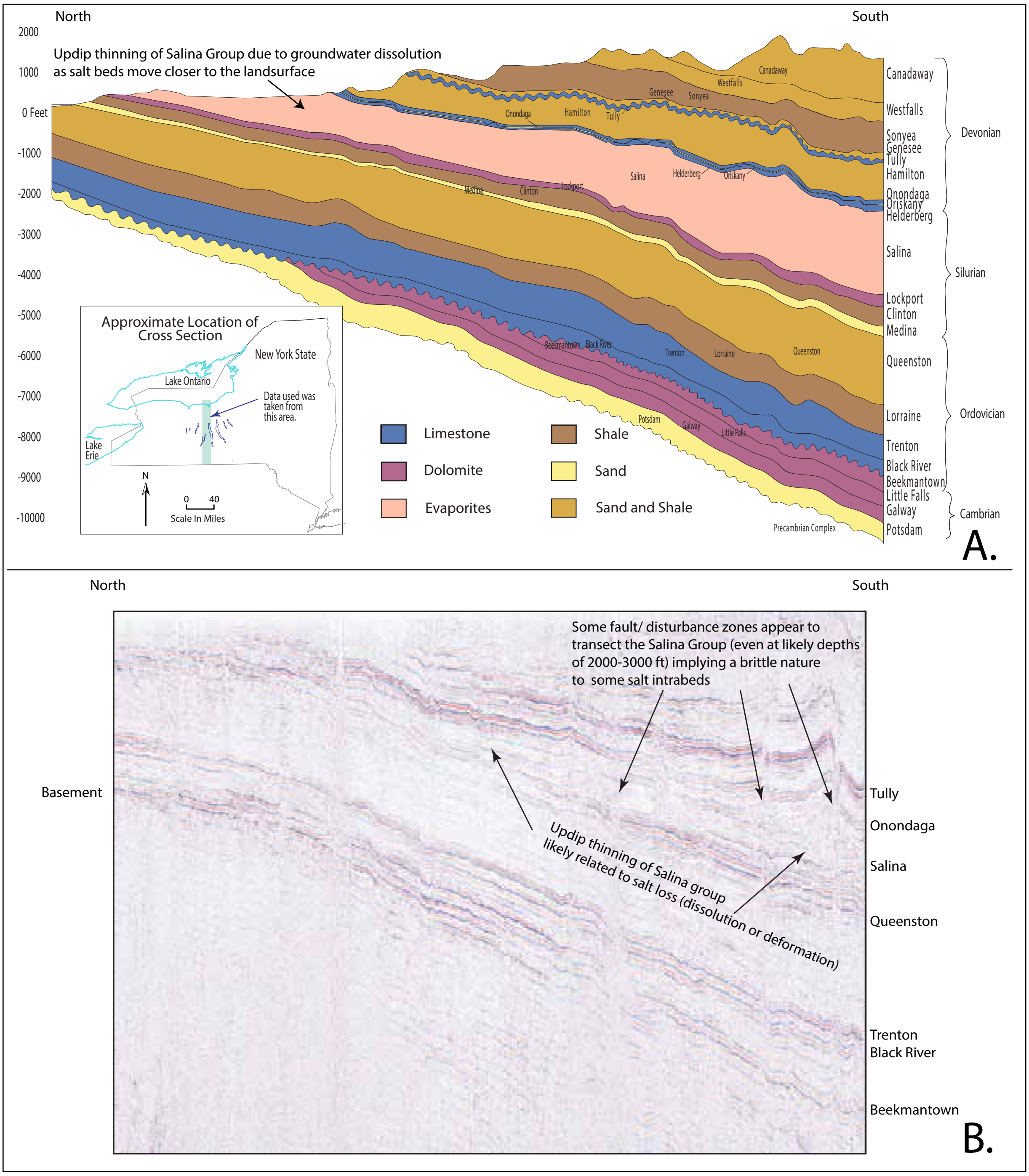

Figure 6. Beds of the Salina Group (including salt layers) dip or deepen to the south, as shown in: A) the stratigraphic cross section and B) a regional seismic line - this line was published without a position or a scale to maintain commercial confidentiality. As the beds of the Salina group approach the surface the total thickness of the unit lessens, likely due to the natural dissolution of the salt layers. This implies there is a natural supply of brine to the shallow parts of the stratigraphy (base images extracted from Smith et al., 2005).

m) in north-central Pennsylvania in Tioga and Bradford Counties (Figure 3). Salt beds in the Salina Group can occur in both the Syracuse and Vernon formations and so are informally termed the Cayugan salts.

All beds in the region of Cayuga Lake show a consistent gentle southerly dip, as seen in the stratigraphic cross section and the north-south seismic line illustrated in Figure 6. This section has a high vertical exaggeration so the beds appear to deepen steeply. This is a standard geological presentation construct, designed to give the viewer maximum visibility of the various rock units and layers that make up the stratigraphy. Actual dip angles in true scale are much less, and beds would appear much thinner in a true-scale section.

What is interesting in the seismic line is the overall thinning in the strata of the Salina Group as the salt beds approach the surface. This is typical of dipping salt beds worldwide and is a direct indication of the dissolution of the salt layers as they get shallower and come into contact with crossflowing undersaturated groundwaters (Warren, 2016; Chapter 7). This geometry implies that the salt at shallower levels beneath the Seneca Lake region is naturally supplying brines to the aquifer system. At deeper levels, the amount of natural dissolution is far less, and the salt in the Salina Group maintains its integrity and overall thickness. This is likely one of the reasons why not all of the salt layers are present in the Salina Group at shallower depths, and one of the main cause of changes in bed thickness at shallower levels (Goodman et al., 2011). The other is deformation related to regional tectonics. Salt dissolution is why any study of the suitability of the salt beds for mining or gas storage in the Finger Lakes will show salt character improves to the south as the salt deepens and is less susceptible to groundwater induced dissolution.

Groundwater dissolution means individual layers and overall salt thickness increase in a southerly direction and why there is a widespread reservoir of dissolution-derived brine beneath and adjacent to the Onondaga Escarpment.

In the past, brine wells drilled to extract a brine feedstock have exploited this brine reservoir (Goodman et al., 2010). Many caverns were created during this time of "wild brining" in the 1800s were allowed to expand to the point where the landsurface became unstable with some cavities daylighting and other exacerbating the creation of "mudboils" still active in the Tully Valley today (Kappel et al., 1996). This landscape instability occurred because "wild-brine" solution caverns were allowed to expand, uncontrolled ,to transect a number of intrasalt beds. Operators continued to operate the brine well as long as the well continued to supply a brine-stock. Once a salt cavern roof was breached (out-of-salt situation) and lost seal integrity, the resultant roof collapse led to a loss of brine well control, so the well was abandoned, and a new brine well was drilled nearby. Since the 1960s, maintenance of solution brine well integrity and minimisation of roof collapse became the aim of most brinefield operators, with the exception of wild-brine well operations in the former Soviet Union and its satellite states (Warren 2016, Chapter 13).

The practice of uncontrolled brinefield expansion and consequent well abandonment has led to later problems atop former brine fields. Worldwide, some brinefield salt cavities, once out of the salt, continued to expand for decades after the causative well was abandoned. Cavities became so large they stoped to the surface to become collapse dolines, with associated loss of life and property (see Warren, 2016; Chapter 13 for case histories). A problem with salt cavity-related collapse and groundwater contamination associated with stoping caverns is that they may not become obvious until many decades after brine or salt extraction operations have ceased. Complete removal of salt layers by uncontrolled brinefield operations in the early part of last century led to the current problems with mud boils in Tully Valley, Onondaga County, New York (Kappel et al., 1996).

Across New York State the buried salt layers in the Salina Group range in purity and thickness, along with the number of intrasalt beds. Targeted layers are ideally more than 95% pure NaCl. Regionally the salt beds beneath New York State contain higher proportions of impurities than their lithostratigraphic equivalents in the Michigan Basin. Salt layers in the Michigan and Appalachian basins are separated by shales and fractured dolomites and variably capped by a unit with abundant anhydrite ($CaSO_4$), which in combination are locally described as the Bertie Formation or the Bertie Group (Figure 5).

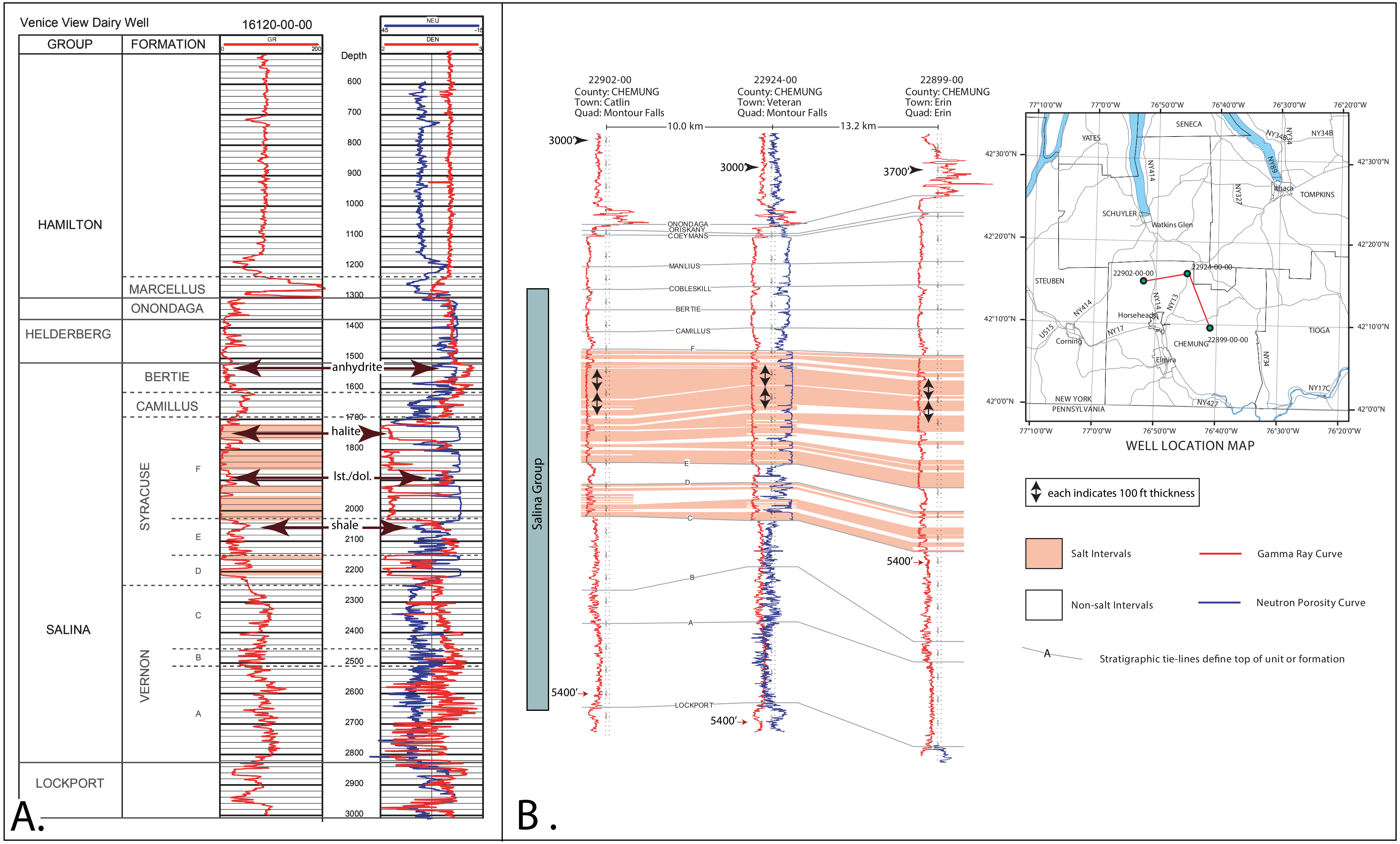

Figure 7 Wireline character of the Syracuse Formation. A) Wireline interpretation of salt interval in Venice View Dairy well, with intervals selected to demonstrate wireline determinants of mineralogy (Base log image extracted from Smith et al., 2005). B) Salt correlation panel based on wireline log measures in three wells located south of Cayuga Lake (base images extracted from Smith et al., 2005).

The lateral and vertical extent of impurities and thickness of salt intrabeds south of the Cayuga Lake region is given in published examples of wireline log data, as in Figure 7a, b. Wireline logs are geophysical measurements of rock properties in a well bore. They are measured by a string of tools lowered on a cable (or wire) into a wellbore and then raised to the surface at a constant rate of rising, as measurements of rock properties are made.

The gamma log measures natural radioactivity in the rock, values tend to be high in shales and low in salt and carbonates (limestones and dolomites) that lack impurities. The density log measures electron density and converts it to equivalent rock densities. Anhydrite has a characteristic high-density value around 3, halite is around 2, while the densities of the other rock types vary according to porosities and matrix constituents. The neutron log measures hydrogen content. When the neutron log and density logs are overlain on a standardised scale, as done in Figure 7a, then regions where the two trackways overlap indicates a likely limestone, some separation indicates dolomite, while a broader separation of tracks indicates shale. A reversal of the dolomite and shale overlap direction indicates a likely sandstone. Wireline interpretation techniques are used to better understand lithology throughout the oil industry and is increasingly in use by the mining industry. Wireline interpretation minimises the need to collect core, which is an expensive process. However, cores preserve rock textures indicative of strength properties and vectors that need to be understood for reliable and safe mining practice.

Figure 7b is an example of the use of the wireline data to correlate the extent of the salt and nonsalt intervals between three wells south of Cayuga Lake. It clearly shows that the salt thickness is not consistent between wells and that the amount and thickness of nonsalt beds vary between wells. The diagram is drawn with the intent of maximising a bed-parallel correlation of intrasalt units between the various wells. There is no control on the orientation of the beds between the wells other than an assumption that the intrasalt beds are aligned sub-horizontally. This is standard geological practice in the oil industry. However, regional observations as seen in published seismic and public-domain core and mine-based observations (detailed in Warren 2015) all suggest intrabed extents and dips within the Cayugan salt are far less predictable than such highly interpretive correlation panels suggest. A comprehensive suite of logs was collected in the drilling of Corehole #18 and paper copies of the log outputs are in the public domain as part of the contents of the RESPEC (2013) report.

The seismic line illustrated in Figure 8 shows the Salina Group geometry in the vicinity of a fault zone and how the salt body it carries can show substantial thickness changes, especially in zones of tectonic disturbance and deformation. This is clearly unlike the evenly-bedded near-constant-thickness salt layers that typify salt occurrences in the Michigan Basin. The salt in the Salina Group in its current eastern extent beneath New York State and Pennsylvania is variably deformed, with resulting thickness changes in individual salt layers (as can be seen locally in the Cayuga Mine (Prucha, 1968) and discussed further in next section of this report. This deformed region includes strata beneath the Fingers Lake region, as indicated by the shaded rectangle in Figure 8.

Thus, the salt beds of the Seneca Lake region and its surrounds are intensely folded into a series of local east-west anticlines and synclines, with elevation differences of more than tens of feet from crest to crest in local folds in the Cayuga mine area (Jacoby, 1963). However, as the published seismic shows, there are much greater lateral thickness changes in the salt across faulted regions, and it is likely that some of these faults have locally penetrated the Salina Group (Figure 8).

Regionally, as first expressed by Gwinn (1964), the various anticlines in the Finger Lake region, and regions further south, are the principal products of halokinetic deformation. The various salt-cored anticlines and synclines (including the Firtree Anticline which transects Lake Cayuga in the vicinity oof the Salt mine - Prucha, 1968) extend downward to the décollement (slippage) surface near the base of the salt layers in the Salina Group. Currently, a dip slightly in excess of 1° is present at the base of the Salina Group; this is true from the vicinity of the Finger Lakes region to the structural front of the collision belt at the Muncy anticline in Sullivan County, Pennsylvania. In this distance of approximately 85 miles, the base of the Salina Group drops from 1,000 ft below sea level near Himrod, New York, to more than 10,000 ft below sea level west of the Muncy anticline.

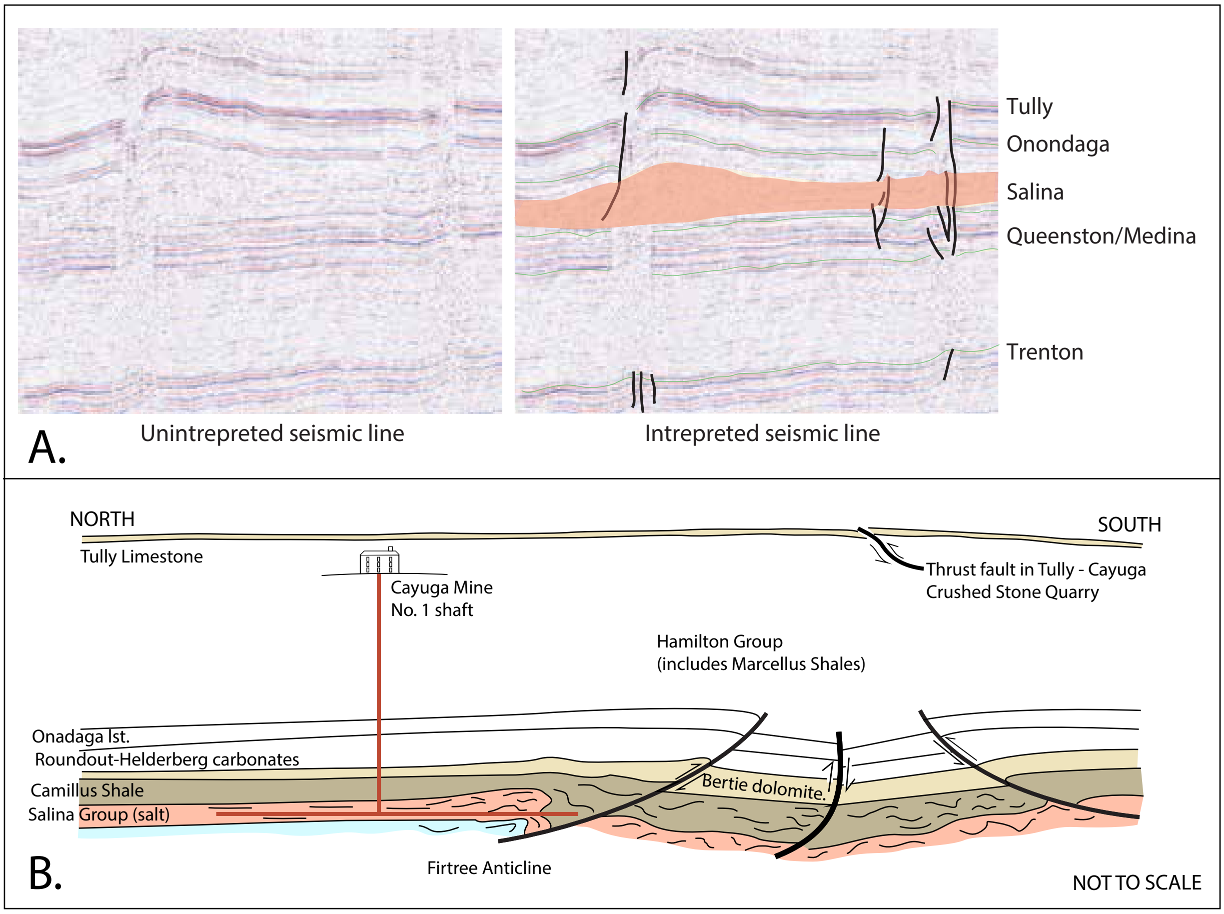

Figure 8. Regional variations in salt thickness (in the Salina Group) as interpreted in A) Seismic (from Smith et al., 2005) and B) an interpretive schematic based on regional thickness changes seen in wells and observations in the Cayuga Mine (after Goodman and Plumeau, 2004a, b).

Down this incline, sliding of post-salt beds likely formed the salt-core anticlines, with characteristically over-steepened and thrust-faulted south-east limbs (Figure 8; Frey, 1973). This leads to the contrast in deformation style seen in Figure 8. Above the base of salt, the beds are folded and deformed, while below the base of salt the beds are gently dipping. Hence, salt and incompetent shales in the Salina Group have flowed plastically during regional tectonic events in the Mesozoic era. This gives rise not only to the intense folding in and above the salt level but also to faulting of the salt and supra-salt section (Figure 8a).

The upper surface of the salt and its overlying sediments in the vicinity of Cayuga and Seneca lakes are characterised by broad, east-west synclines and anticlines, with axes paralleling the sharp folds and salt-cored deformation zones in the underlying evaporites. In contrast, beds below the décollement or slippage layer near the base of salt are not folded. This structural contrast, in combination with ongoing natural salt dissolution in the shallower regions, and an earlier episode of dissolution tied to the Alleghanian Orogeny explains why the wedge-shaped plate of post-salt rocks thins from about 12,000 ft thick near the structural front to less than 2,000 ft in the Cayuga Rocksalt Mine (Frey, 1973; Harrison et al., 2004). Based on a regional study of fault trends and seismic events in New York State, Jacobi (2002) concluded, "...It thus appears that not only are there more faults than previously suspected in NYS, but also, many of these faults are seismically active..." This question of ongoing fault activity should be addressed in terms of mine expansion toward the north of the current operational area of the Cayuga Salt Mine and we shall return to it once we have discussed the nature of the brine hydrology within its evolving Quaternary glacial-interglacial context.

Lake	Length (km)	Width (km)	Elevation (m msl)	Water volume (10^6 m^3)	Surface area (SA) (km^2)	Drainage area (DA) (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

Quaternary Geology of the Finger Lakes region of New York State.

The Finger Lakes of central New York State consist of 11 elongate, glacially scoured lake basins Mullins et al., 1996). Located south of Lake Ontario (Figure 9a) along the northern margin of the glaciated Appalachian Plateau, the Finger Lakes have been eroded into undeformed, but well-jointed, Devonian sedimentary rocks (chiefly shale) that dip gently to the south-southwest. 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 9a). 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's width exceeds 5.6 km (3.5 miles); Lake Cayuga is 61 km (38.1 miles) long with a surface area of 172 km^2 (66.4square miles), while Seneca at 175 km^2 (66.9 square miles) is the largest of the lakes in of water surface area (Table 1). Glacially-driven sub-ice base erosion was most intense beneath Seneca and Cayuga lakes, where maximum depths to bedrock are 304 m and 249 m below sea level, respectively. The ice-retreat model currently used to explain the formation and filling of the various Finger Lakes is illustrated in Figure 9c (Mullins et al., 1989, 1996).

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 9a, b). The uplands between the Finger Lakes are covered by a thin layer of till with a series of distinct chevron-shaped till moraines (Figure 9b), which become more laterally continuous to the north. Immediately south of the Finger Lake basins, and restricted to the valleys, are kame moraines (Figure 9a) collectively referred to as the Valley Heads Moraine. The 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-laid drift (Figure 10a).

Hydrology of the Cayuga Lake region

Deep subsurface brine hydrology and hydrochemistry in the Cayuga Lake region is strongly influenced by a combination of two process sets; 1) longer-term ongoing deeper salt unit dissolution and natural aquifer salinization and, 2) a shallower set of hydraulic flow reversals responding to pressurization changes driven by loading and unloading fluctuations, in response to the to and fro and ultimate retreat of Late Quaternary ice sheets (Laurentide sheet; Goodman et al., 2011).

The two process sets are now discussed and then their significance outlined in terms of depths of associated induced brine permeability and implications for possible aquifer connection between deep saline aquifers and shallower fresh water units.

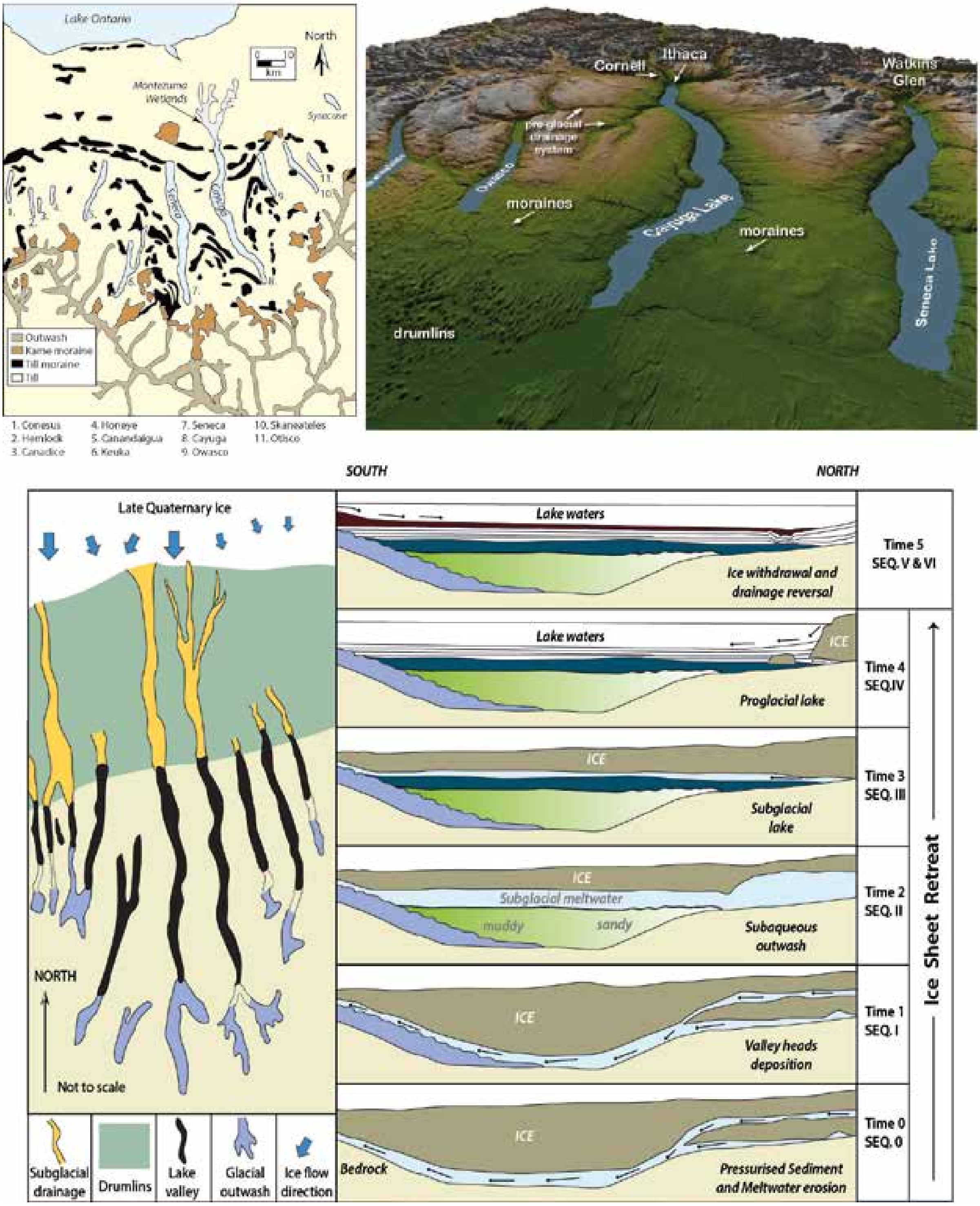

Figure 9. Finger Lakes, upper New York State. A) locality and general surface geology (after Mullins et al., 1996). B) Topography of the Cayuga Lake region looking South (extracted from images downloadable John Allmendinger's website <www.geo.cornell.edu/geology/faculty/RWA>. C) Geological model explaining Finger Lake formation as subglacial scour freatures (after Mullins et al., 1989).

Saline aquifers and glacial drivers of fluid entry

Worldwide, wherever bedded or halokinetic salt approaches the land surface it dissolves and, unless in an extremely arid region, the salt unit rarely makes it to the surface (Warren, 2016). Accordingly, regions of salt sub-crop are typically characterised by saline groundwaters and suprasalt depressions in the landscape, with adjacent ridges composed of less soluble sediments such as limestones or sandstones. This is the case where the Silurian Saline Group saline sediments subcrop downdip of the Onondaga escarpment, which is located immediately north of the Finger Lakes region (Figure 11; Goodman et al., 2011)

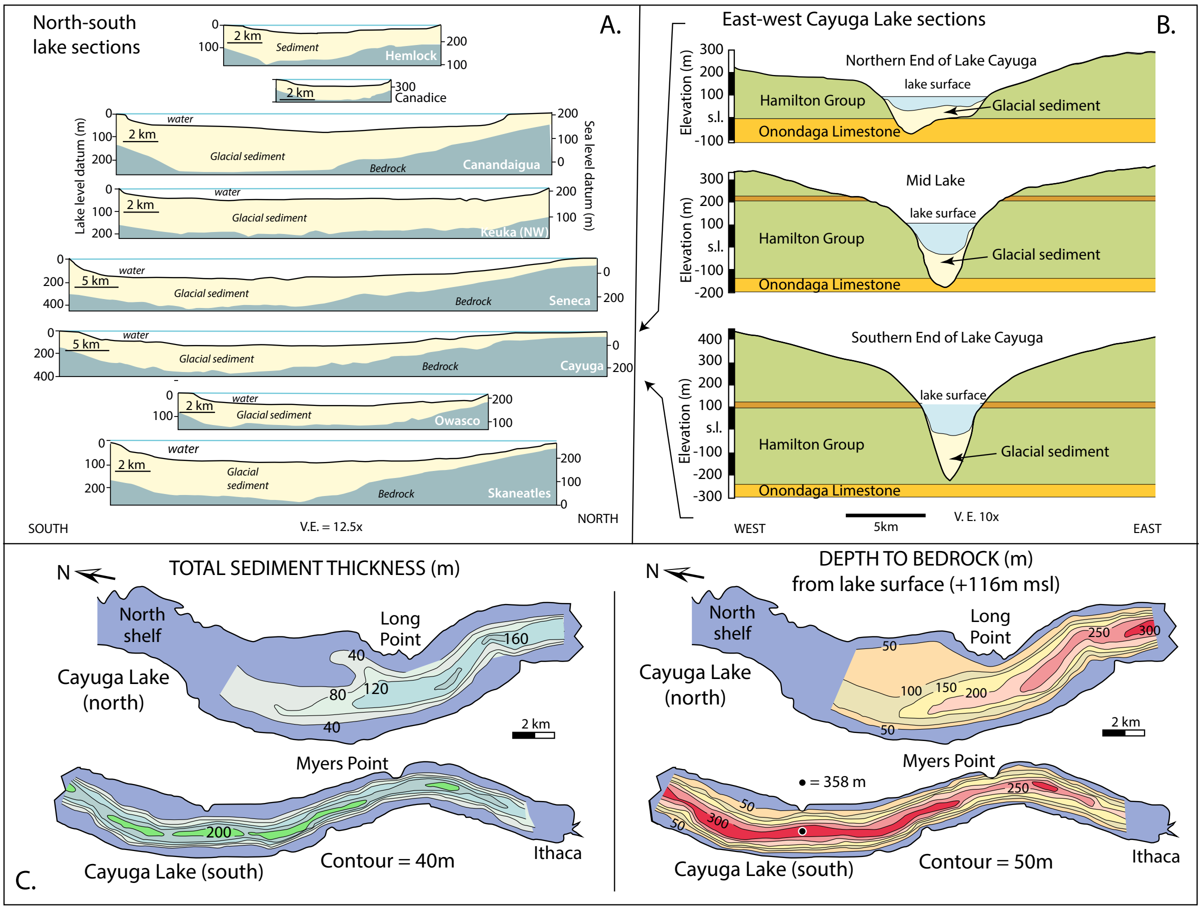

Figure 10. Section and map views of sediment fill statistics (after Mullins et al., 1995) A) Total thickness of the glacial sediment fill in the various Finger Lakes. B) Variation in position of penetration in the Phanerozoic stratigraphy of the glacially scoured valley-base in east-west sections (based on seismic) at the northern, medial and southern end of Lake Cayuga. C) Total thickness isopach of glacial sediment fill (m) and depth to bedrock isoclines relative to lake water surface (based on seismic interpretation).

This region of saline groundwaters, created by Salina salt unit dissolution, and accessible by the brine technologies of the time defines the area where salt was manufactured from various natural salt springs and shallow wells, beginning in the 1790s and ongoing throughout the 1800s (Merrill et al., 1893)

Work by Goodman et al. (2011) described the brine aquifer of this region as being of likely glacial origin and associated with downdip salt dissolution. The system is situated in the up-dip portions of the Silurian Salina Group subcrop belt, south of the historical salt manufacturing center at Montezuma, Cayuga County, New York (Figure 11). Well completion records report saline formation water in the interbedded shale, carbonate and salt sequence. If accurately reported, fluid emplacement in these strata was not vertical driven; rather an iceweight-induced lateral down-dip migration is required to emplace undersaturated fluid beneath and between partially intact salt beds which acted as aquitards or aquicludes. Increased hydraulic gradients imposed by glacial ice during the Pleistocene Epoch likely promoted enhanced, southward-directed downward fluid flow along bedding-parallel transmissive horizons within the Salina Group. Such saline fluids of variable salinity are reported in Salina Group strata to subsurface depths of about 1,500 feet. At more substantial depths, most Salina Group strata do not flow water. These hydrogeological patterns are in conflict with a Tothian model of basin-scale fluid flow that requires meteoric recharge (rain and snow-melt) in the Appalachian Plateau (Southern Tier) Province of western New York to infiltrate as deeply as the Salina Group salts before migrating northward and discharging as brine in the Lake Ontario Plain. Instead, water-bearing Salina Group strata are restricted to a belt approximately 18 miles south of, and parallel to, the Onondaga Escarpment. Hence, the saline aquifer, referred to herein as the Montezuma Brine Aquifer System (MBAS), more likely owes its origin to Pleistocene paleohydrological processes that affected the escarpment.

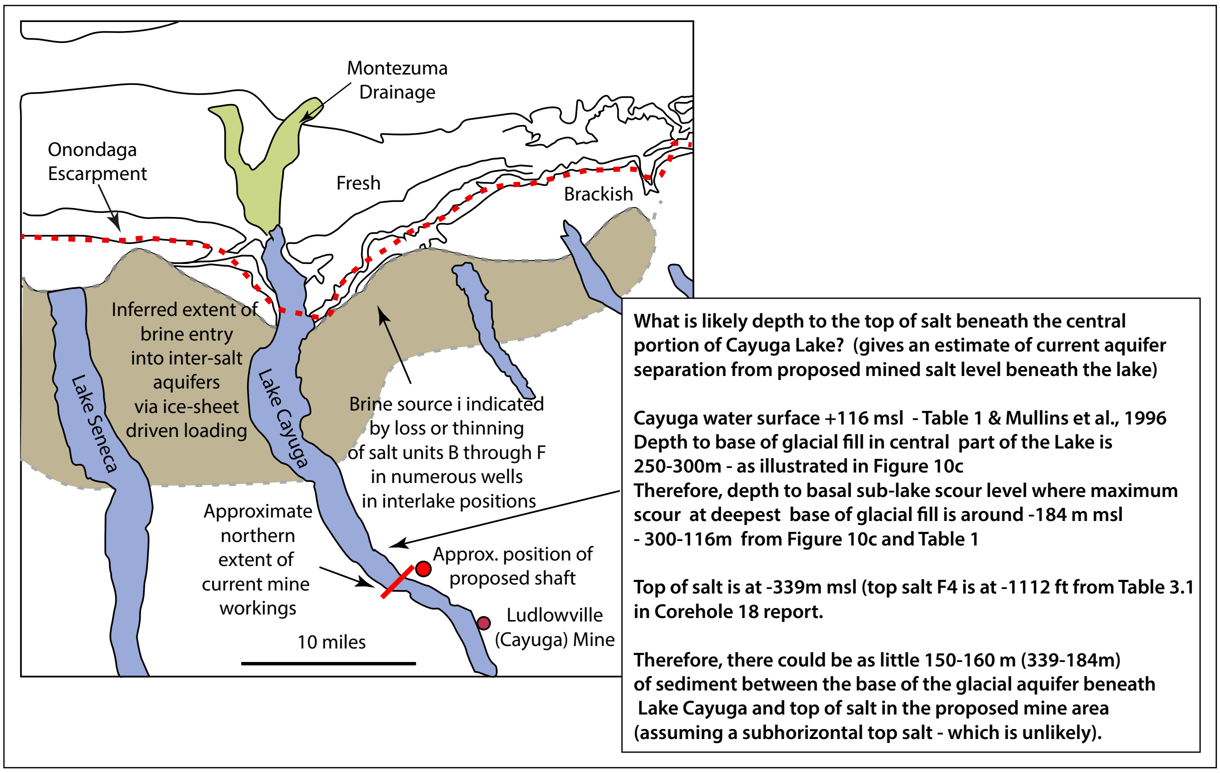

Figure 11. The extent of subsurface dissolution of various Syracuse Fm salt beds as the regional geology shallows toward the north infleuence region is shaded brown. The intersalt hydrology was periodically pressurised and released by expansion and retreat of glacial ice (after Goodman et al., 2011). The extent of the brown shade area is based on wireline signatures in wells drill in interlake positions. None of these wells (which are petroleum wells) were drilled into saline sediments below the glacial scour base thalweg. The inset box gives a calculation of the likely distance separating active undersaturated pore waters held in aquifers in the glacial sediments and the top salt unit, beneath the central part of Cayuga Lake, based on material presented in this report.

During the period of Pleistocene glacial advance, the MBAS was mainly closed-ended along its southern boundary, i.e. the aquifer had no discharge zone but maintained its high salinity by dissolving the upper and lower edges of the southward-dipping salt beds. Recharging sub-glacial meltwater simply may have infiltrated further down-dip through bedding-parallel transmissive zones and remained in storage maintained in position by the ice loaf at its up-dip end. The term "pocket" aquifer is proposed for this type of closed-ended, glacio-hydrogeological system.

Following glacial retreat, the steepened, southward-directed hydraulic gradient dissipated, and the source of cold water recharge was removed. Thus, according to the glacial pocket aquifer hypothesis, the Salina Group outcrop belt changed behaviour over time from a Pleistocene recharge zone to a Holocene discharge zone. Today, the Salina Group outcrop belt is populated by brine springs, confirming its status as a discharge zone for the modern MBAS.

In proximity to the Onondaga Escarpment, a localised, shallow subsurface, topographically controlled flow system contains fresh water. The saline water in the deeper subsurface MBAS is likely driven up-dip to the line of saline springs by a gradual release of residual Pleistocene fluid pressure. Fresh water and saline water springs can be closely juxtaposed, and the waters from the shallow and deeper flow systems likely mix in many areas along the southern margin of the Lake Ontario Plain.

According to Goodman et al. (2011), the presence of brine in subsurface Salina Group strata south of the Onondaga Escarpment in western New York is commonly reported in the vintage scientific literature. Hence, the saline aquifer system is likely more extensive than the Seneca and Cayuga Lake valleys near Montezuma. Nineteenth-century descriptions of salt wells in Wyoming, Livingston, Genesee, Erie and Cattaraugus Counties indicate artesian brine conditions in a zone parallel to, and south of, the up-dip terminus of the salt beds in the Salina Group. The salt beds are preserved just south of the Onondaga Escarpment beneath much of western New York. North of the escarpment, the Salina

Group strata are so shallow in the subsurface that they are thoroughly leached by actively circulating groundwater, and the salt beds have been fully dissolved.

This ice-load driven flow of brine in and out of beds in contact with the fluctuating edges of glacial ice sheets does not just occur in the Finger Lakes region, but also occurs in fractures in hard-rock (granite and granodiorite) terrains in the cratonic shield regions of Canada, Greenland and Antarctica where it drives seawater-derived brines into the craton to depths of 1 km or more (Figure 12; Warren, 2016, Chapter8; Starinsky and Katz, 2003). In such cases the load induced by a kilometer or more of ice cover drove additional fracturing in the underlying strata, This mechanism drives fluid entry further into rock areas that would otherwise be impermeable.

What makes the Finger Lakes region unique in terms of its ice-load driven hydrology is the fact that the brine entry is penetrating and dissolving a set of soluble sediments (dissolving salt layers separated by the carbonate and shale aquifers). This is somewhat different the more commonly invoked sea-edge ice sheet setting driving brine entry (Figure 12). This style ice sheet loading enhancing salt bed dissolution is active along the northern end of Lake Cayuga and explains the complete disappearance of shallower salt beds in the northern part of the subsurface geology beneath Lake Cayuga (Figure 11). Ice sheet loading may also have enhanced fracturing of intrasalt carbonate beds and perhaps driven a degree of recent salt flow in regions of significant local differences in salt thickness. These thickness differences were originally due to earlier folding and deformation (Warren, 2016; Chapter 6 for a summary of the physics of salt deformation).

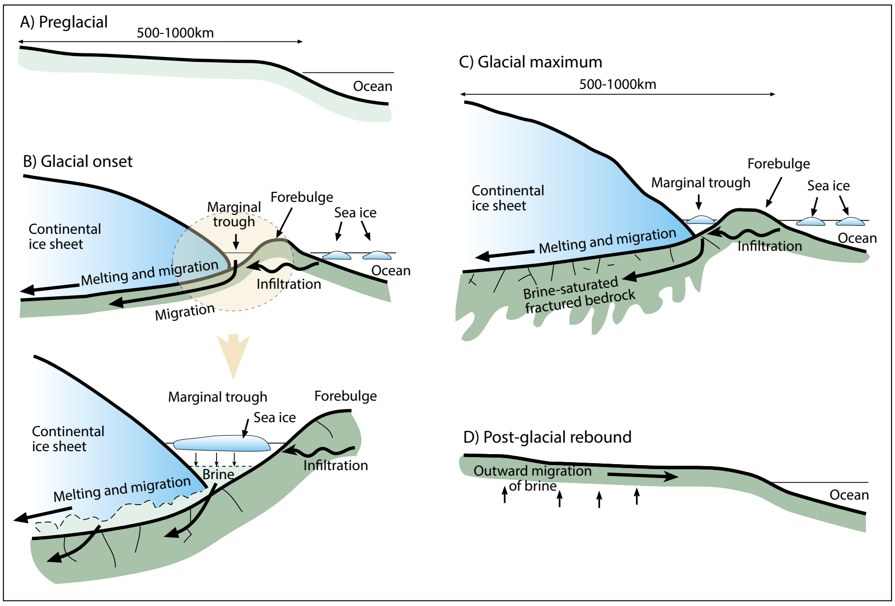

Figure 12. Isostatic and hydrological evolution of a marine-cryogenic basin aquifer system: A) Continent-ocean boundary before the onset of a glacial cycle. B) An ice sheet develops on the continent, depressing the crust underneath and forming a forebulge along the coast. Seawater infiltrates into the 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).

Salt mine problems due unforeseen water entry

Salt mining is usually safe and predictable. However, there are some situations, illustrated by the following case histories that are relevant to the Cayuga mine situation. We shall consider three salt mines, namely; 1) loss of the Retsof Mine, 2) the Lake Pegnieur collapse and loss of the Jefferson Island Salt Mine 3) the flooding of the Patience Lake Potash Mine. All three mines were lost to flooding due to workings interacting with unexpected aquifer systems (See Warren 2016, Chapter 13 for other examples).

Retsof Mine, New York State, USA

The 1994 flooding of the Retsof Mine, New York State USA, took place over a period of weeks. Before abandonment, the 24 km^2 area of subsurface workings made it the largest underground salt mine in the USA and the second largest in the world (Figures 13, 14). The mine had been in operation since 1885, exploiting the Silurian Salina Salt and each year it produced a little

Figure 13. 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).

over 3 million tons of halite. It supplied more than 50% of the total volume of salt used to de-ice roads across the United States.

The eventual loss of the Retsof Salt Mine 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. 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 13) 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^3/min, via the overlying now fractured limestone back (Gowan and Trader, 1999).

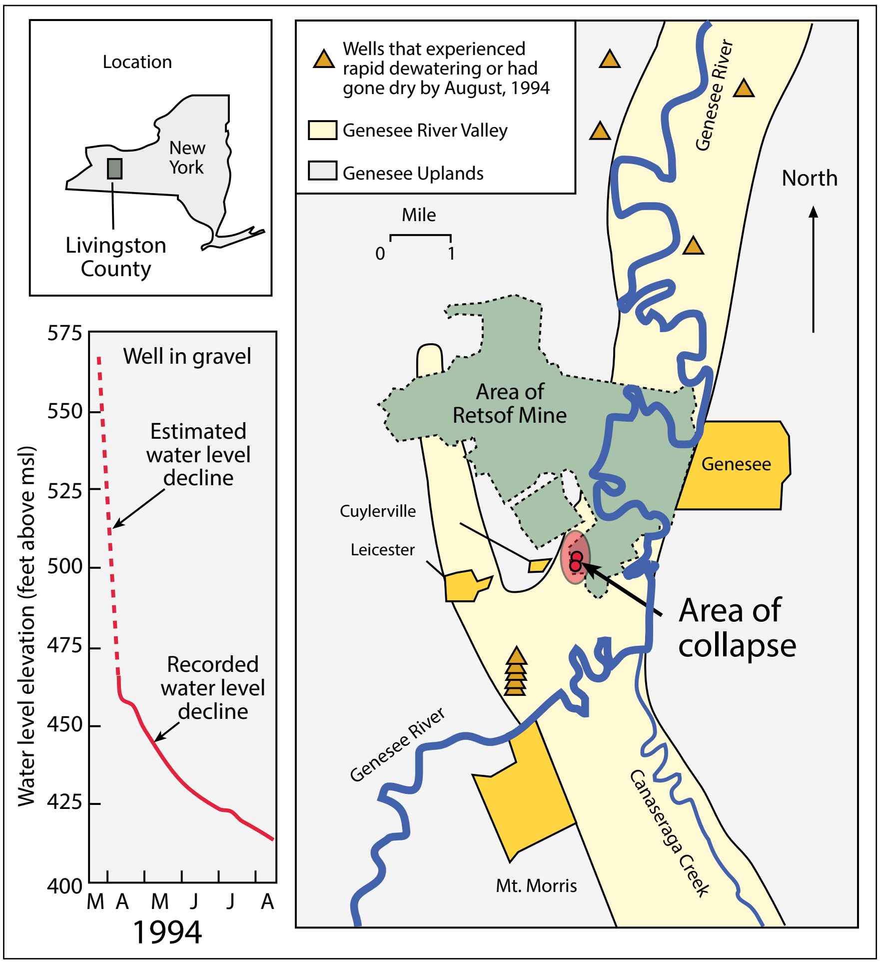

Figure 14. Locality plan of the Retsof mine and the area of collapse along with a selected hydrograph from a well in the Genesee River valley (March 12 to August 12 1994; after Tepper et al., 1997).

In a little more than a month, two steep-sided circular collapse features, some 100 meters apart, had indented the landscape above the two collapsed mine rooms (Figure 14. The northernmost 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 13). 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 a number of local wells in the months following the collapse; some dried up (Figure 14; Tepper et al., 1997). Aside from the loss of the mine and its effect on the local economy, other 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. Land subsidence, possibly related to compaction induced by aquifer drainage to the mine, even occurred near the town of Mt. Morris some 3 miles southwest of the collapse area.

Post-mortem examination of closure data from the two failed mine panels showed an anomalous buildup of fluid pressure above the panels in the period leading up to their collapse. The initial influx of brine and gas following the first collapse coincided with the relief of this excess pressure. Gowan and Trader (1999) demonstrated the existence of pre-collapse pressurised brine cavities and gas pools above the panels and related them to nineteenth-century solution mining operations. They also documented 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 the landscape low that defined the Beard Creek valley (Figure 13). Brine accumulations apparently formed in natural sinks, long before solution mining began in the valley, driven by the natural circulation and accumulation of meteoric waters along vertical discontinuities, which connected zones of dissolving salt to overlying fresh water aquifers. Subsequent work by Gowan and Trader (2003) showed that

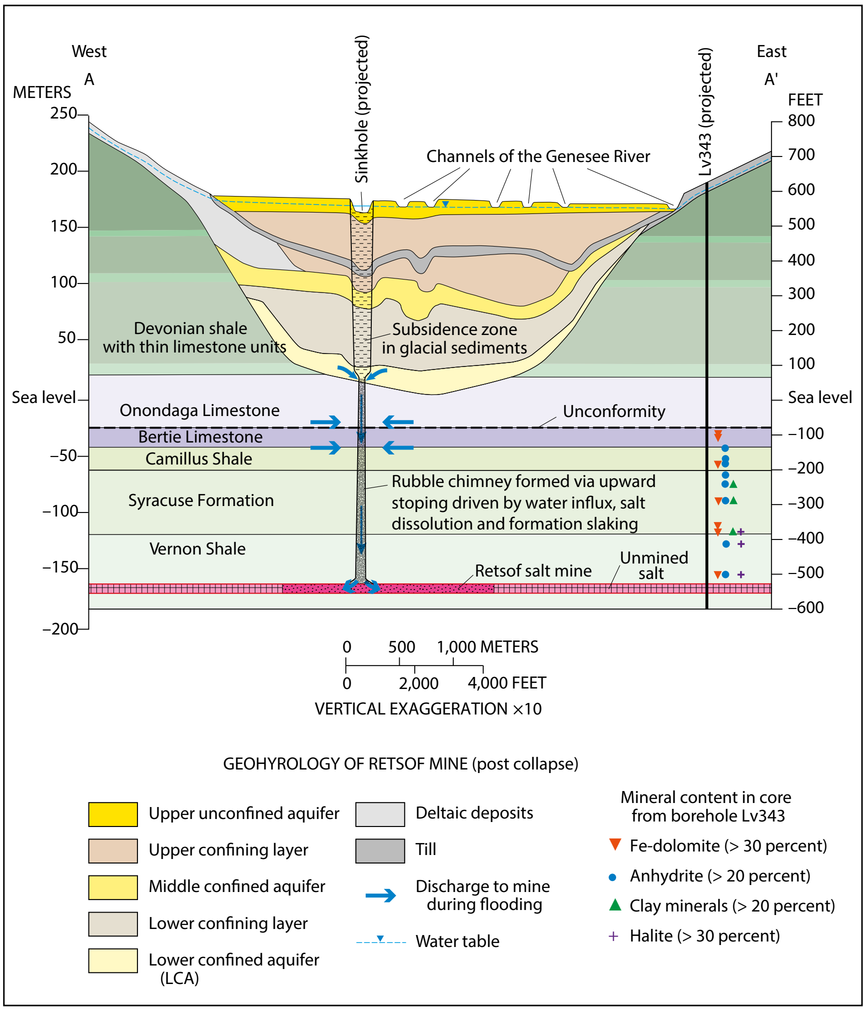

Figure 15. Stratigraphic section depicting rubble chimney above collapsed room in Retsof salt mine, Livingston County, N.Y. Also shown are the main aquifers that facilitated water influx into the flooding mine (inflow also drained natural and artifical brine filled solution cavities in the stratigraphic levels above the working mine level (after Yager et al., 2009)

daylighting sinkholes had formed by the down-dropping of the bedrock and glacial sediments into voids created by the dissolution of salt and the slaking of salt-bearing shale upon exposure to fresh water.

This collapse took place in a salt-glacial scour stratigraphy and hydrology near identical to that in the Cayuga Mine region. In this context, it is of interest to note that there are a number of documented plugged and abandoned brine wells located in the vicinity of the Cayuga Mine that were drilled from the 1890s to the 1950s. Figure 1b plots the positions of these known wells.

One wonders if there are older undocumented wells on the eastern lakeshore located in areas where the salt brine target was shallower further north. Such undocumented brine wells would likely have been sited near the lake shore to facilitate the transport of the brine product. Current salt mining below the lake avoids the possibility of intersecting solution cavities associated with any such undocumented old brine wells. But, the drive needed to position the pilot hole for Shaft #4 will transect a salt region that may have been solution-mined more than a century ago. A seismic or a less disruptive "mini-sosie" survey should be undertaken to identify any possible solution cavities in the region that will connect the current workings to the Shaft #4 pilot hole.

Lake Peigneur, Jefferson Island, Louisiana

On November 20, 1980, one of the most spectacular sinkhole events associated with oil-well drilling occurred atop the Jefferson Island salt dome. On that day Lake Peigneur disappeared as it drained into the workings of the underlying Jefferson Island salt mine. In a few hours a collapse sinkhole, some 0.91 km^2 in area, had daylighted in the southeast portion of the lake (Figures 16, 17; Autin, 1984, 2002; Warren, 2016). In the 12 hours following the first intersection of the drill hole with the mine workings, the underlying mine was completely flooded, and Lake Peigneur was completely drained.

Drainage and collapse of the lake began when a Texaco oilrig, drilling from a pontoon in the lake, breached an unused section of the salt mine some 1000 feet (350 meters) below the lake floor (Figure 17). Witnesses working below ground described how a wave of water instantly filled an old sump in the mine measuring some 200 feet across and 24 feet deep. This old sump was in contact with a zone of anomalous "black" salt (a boundary shear zone - see Warren, in press, for further discussion of black salt anomalies). The volume of suprasalt floodwater engulfing the mine corridors couldn't be drained by the available pumps. Some 23-28 million m^3 of salt were extracted during the preceding 58 years of mine life. The rapid flush of lake water into the mine, probably augmented by the drainage of natural solution cavities in adjacent anomalous salt zones and associated collapse grabens beneath the lake floor, meant landslides and mudflows developed along the perimeter of the overlying Peigneur sinkhole, so that post flooding the lake was enlarged by 28 ha.

With water filling the mine workings, the surface entry hole in the floor of Lake Peigneur quickly grew into a half-mile-wide crater. Eyewitnesses all agreed that the lake drained like a giant unplugged bathtub—taking with it trees, two oil rigs (worth more than $5 million), eleven barges, a tugboat and a sizeable part of the Live Oak Botanical Garden. The drained lake didn't stay dry for long, within two days it was refilled to its normal level by Gulf of Mexico waters flowing backwards into the lake depression through a connecting bayou (Delcambre Canal, aka Carline Bayou) forming what was a short-term waterfall with the highest drop in the State of Louisiana. Associated ground movement and subsidence left one former lake-front house aslant under 12 feet of water (Autin, 1984).

The Peigneur - Jefferson Mine disaster had wider resource implications as it detrimentally affected the

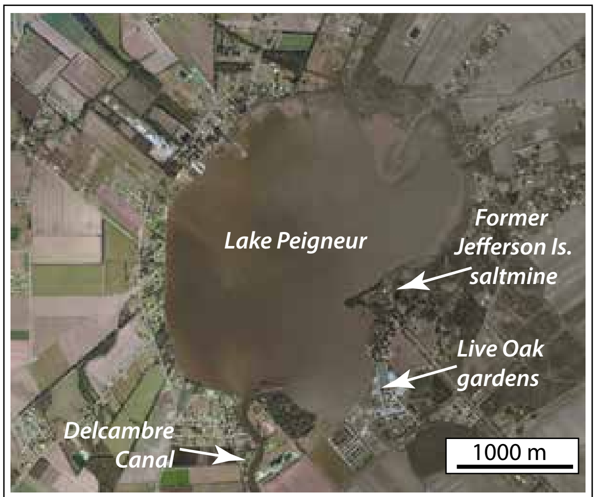

Figure 16. Lake Peigneur, Louisiana (scale ®Bing image mounted in ®MapInfo) see also Warren 2016.

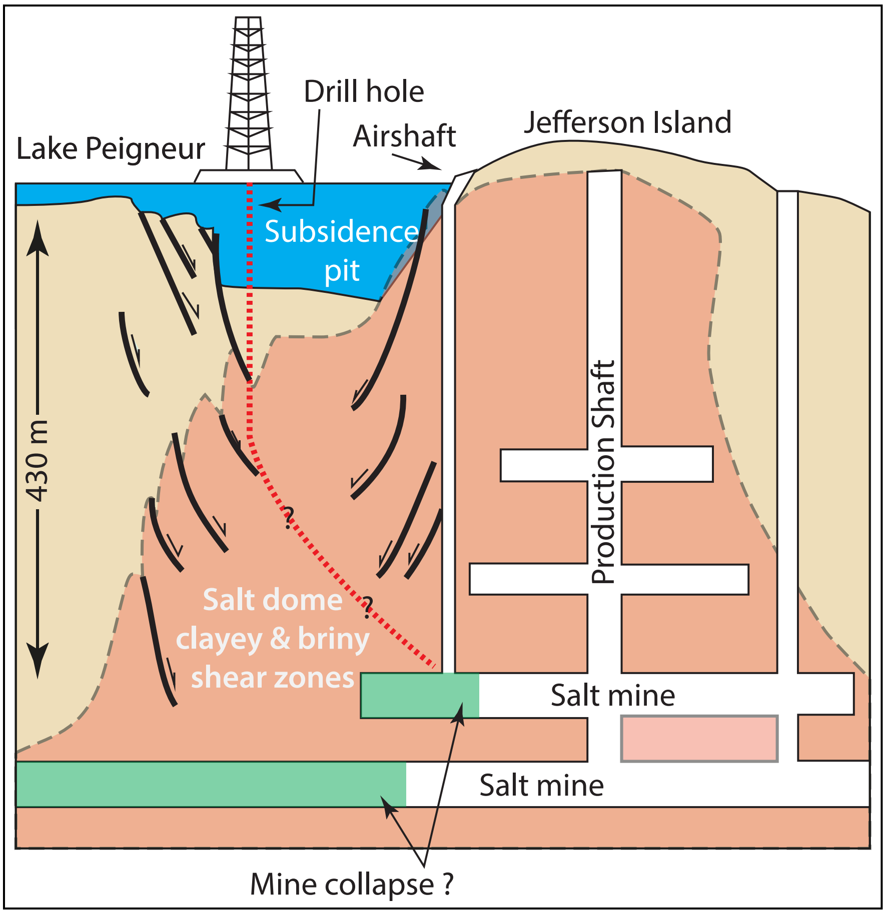

Figure 17. Lake Peigneur, Jefferson Island, cross section showing the cause of the flooding of the mine and the temporary draining of the lake (in part after Keller and Blodgett, 2006)

profitability of other salt mines in the Five Islands region (Autin, 2002). Even as the legal and political battles at Lake Peigneur subsided, safe mining operations at the nearby Belle Isle salt mine came into contention with public perceptions questioning the structural integrity of the mine roof. During ongoing operations, horizontal stress on the mineshaft near the level where the Louann Salt contacts the overlying Pleistocene Prairie Complex across a zone of anomalous salt-defined aquifer proximity had caused some mine shaft deterioration and salt leakage. Broad ground subsidence over the mine area was well documented and monitored, as was near continuous groundwater leakage into the mine workings. The Peigneur disaster meant an increased perception of continued difficulty with mine operations and an increased risk of catastrophic collapse related to salt anomaly intersections was considered a distinct possibility. In 1985, a controlled flooding of the Belle Isle Salt Mine was completed, as part of a safe closure plan.

Subsidence over the nearby Avery Island salt mine (operated by Cargill Salt) has been monitored since 1986 when small bead-shaped sinkholes were initially noticed in the above mine region. Subsidence monitoring post-1986 defined a broad area of bowl-shaped subsidence, within associated areas of gully erosion, likely underlain by BSZ's (Autin, 2002). Avery mine is today the oldest operating salt mine in the United States and has been in continual safe operation since the American Civil War. After the Lake Peigneur disaster, the mine underwent a major reconstruction and an improved safety workover. Subsidence is still occurring today along the active mine edge, which coincides with a topographic saddle above an anomalous salt zone, which is located inside the mined salt area. At times, ground water has seeped into the mine, and there are a number of known soil-gas anomalies and solution dolines on the island above but not in contact the mine. These are natural features that predate mining and are continually monitored.

Much of the subsidence on Avery Island is a natural process as differential subsidence occurs atop any shallow salt structure with the associated creation of zones of anomalous salt (Warren, 2016, Chapter 7). Dating of middens and human artefacts around salt-solution induced, water-filled depressions atop the dome, shows dissolution-induced subsidence is a natural process, as are short episodes of catastrophic lake floor collapse, slumping and the creation of water-filled suprasalt dolines (circular lakes). Such landscape events and their sedimentary signatures have histories that extend back well beyond the 3,000 years of human occupation documented on Avery Island (Autin, 2002).

What the Peigneur-Jefferson Island collapse illustrates, once again, is how an unexpected water breach can have disasters effects on a safely operating salt mine. In this case, the mine operation was not to blame, but the volume of breach waters was probably augmented by the proximity of some parts of the no-longer-active areas in the mine workings to anomalous salt zones and natural brine-filled solution cavities within salt boundary positions.

Patience Lake Potash Mine flood

In the 1970s the Patience Lake potash mine operation, located on the eastern outskirts of Saskatoon, Canada, encountered open fractures tied to a natural collapse structure. Grouting managed to control the inflow and mining continued. Then, in January of 1986, the rate of water inflow began to increase dramatically from the same fractured interval (Figure 18; Gendzwill and Martin 1996).

At its worst, the fractures associated with the structure and cutting across the bedded ore zones were leaking 75 m3/min (680,000 bbl/day) of water into the mine. The water was traced back to the overlying Cretaceous Mannville and possibly the Duperow formations. Finally, in January 1987 the mine was abandoned. It took another six months for the mine to fill with water. Subsequent seismic shot over the offending structure suggested that the actual collapse wasn't even penetrated; the mine had merely intersected a fracture within a marginal zone of partial collapse (Gendzwill and Martin 1996).

Part of the problem was that the water was undersaturated and quickly weakened pillars and supports, so compromising the structural integrity of the workings. The unexpected intersection of one simple fracture system resulted in the loss of a billion dollar conventional potash mine. Patience Lake mine now operates as a cryogenic solution mine by pumping warm KCl-rich brine from the flooded mine workings to the surface. Harvesting of the ponds takes place during winter af ter cryogenic precipitation of sylvite in the at-surface potash ponds (Fig. 19).

Unlike the Patience Lake Mine flood, there was a similar episode of water inflow in the nearby Rocanville Potash Mine. But there a combination of grouting and bulkhead emplacement in succeeded in sealing off the inflow, thus saving the mine (see Warren 2016 for detail). Unlike

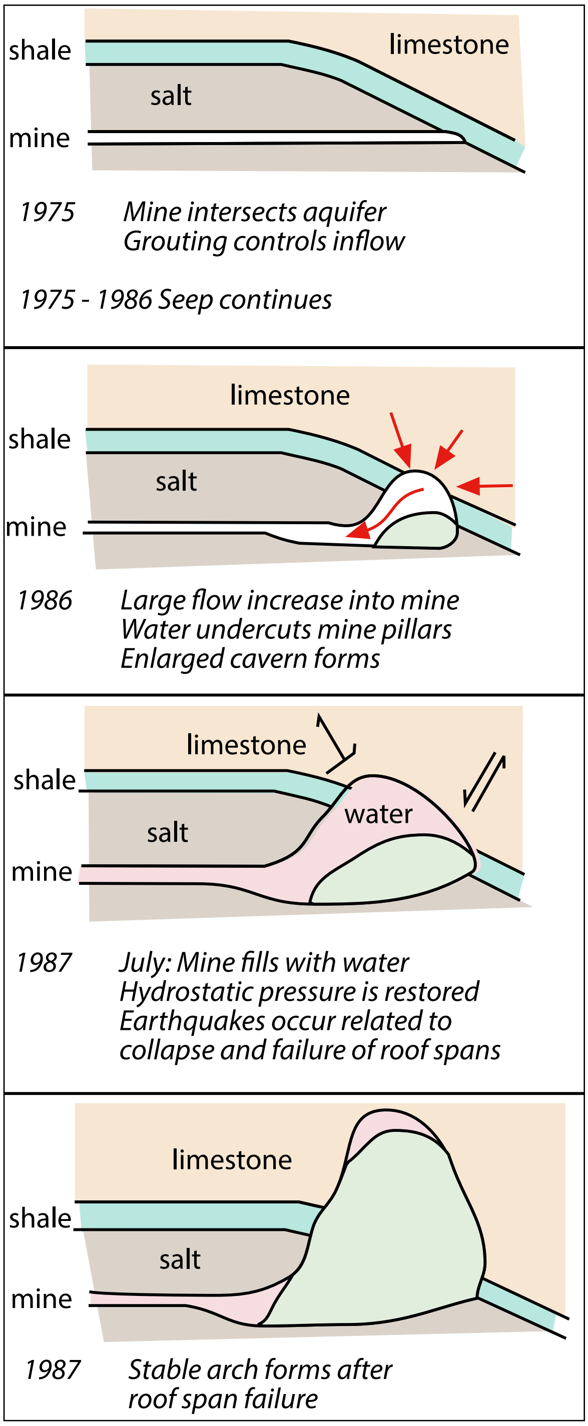

Figure 18. Sequence of events controlling the flooding of the Patience Lake Mine (after Gendzwill and Martin, 1996).

Patience Lake, the brine from the breached structure in Rocanville was halite-saturated, so limiting the amount of dissolution damage in the mine walls. Different outcomes between the loss of the Patience Lake Mine and recovery from unexpected flooding in the Rocanville Mine likely reflects the difference between intersecting a natural brine-filled dissolution chimney that had made its way to the Cretaceous landsurface and is now overlain by a wide-draining set of aquifer sediments, versus crossing a blind dissolution chimney in a saline

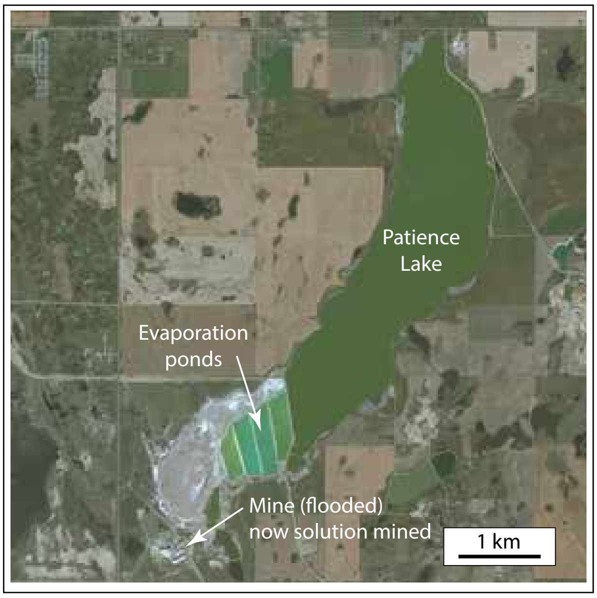

Figure 19. Patience Lake - PCS solution mine, Saskatchewan, Canada

Devonian sediment surround that never broke out at the Cretaceous landsurface. Understanding the nature of the potential hydrological drainages and water source is a significant factor in controlling unexpected water during any mine expansion.

Implications for the Cayuga Salt Mine expansion

The supreme rule for safe, conventional salt mining in bedded and halokinetic ore hosts is "stay in the salt" (Figure 20). Problem areas encountered in most halite and potash mines are related to thinning or disappearing salt-ore seams, usually in zones showing evidence of water-related dissolution and solution collapse. In other words, problems tend to occur when there is an unexpected intersection with a precinct of anomalous salt features (Woods, 1979; Boys, 1990, 1993; Warren, 2016). Uncontrollable water inflow is the greatest threat to any operating salt/potash mine in both bedded and halokinetic ore hosts, as can be seen in the three previous case histories and numerous other examples, as detailed in Warren 2016; Chapter 13.

"Stay in the salt"

As the Cayuga Mine operating face steadily moves further north below Lake Cayuga, the possibility of approaching a sub-lake aquifer increases. This should generate caution in terms mine planning and possible challenges if ongoing operations place parts of the salt mine workings in a condition of aquifer proximity. The same caution should also be considered to be an integral part of the approval process for construction of Shaft #4, which will involve the excavation of a drive across some lateral distance between an existing portion of the mine workings and the base of the construction site for the pilot hole that will ultimately evolve into Shaft #4 (Figure 11).

Current discussion of the geological conditions in the vicinity of Shaft #4 and clarification requests from New York state authorities do not deal with the fact that the floor of the deep glacial scour channel, defining the base of the water filled glacial sediments beneath Lake Cayuga and its overlying water column, has been downcut to depths greater than 300 m below the lake water surface. This is a conservative downcut estimate as Mullins et al. (1996) document a maximum scour depth of 358m in the Lake Cayuga erosional valley (position indicated by the black circle in Figure 10c). The documented level of glacial scour and fill geology is presented as Figure 10b (after Mullins et al., 1996)

The likely vertical distance of separation between top of salt and the lowest scour position of the glacial valley trace (thalweg) beneath the central portions of Cayuga Lake is possibly as little as 150-200 m (see calculation inset in Figure 11). This aquifer-to-salt separation is less than normally considered a safe separation from a potential fresh-water aquifer. A minimum vertical distance of 200 meters+ is considered necessary if the possibility of unwanted water entry into the mine workings is to be minimised. Without knowledge of the lateral discontinuities at the mine level and if any potential intersalt fracture zones are to be intersected during the construction of Shaft #4, reliable prediction of mine stability is problematic.

Cargill Mine operators are already aware of the need to stay away from possible salt anomaly areas, as evidenced by their informed decision to keep a safe working distance from Anomaly D in the Cargill subsurface operations.

What needs further consideration before the construction of Shaft #4 via upward reaming is the possibility of an aquifer connection between the lake waters and the intersected aquifer in Corehole #18. As mentioned earlier, and documented in the RESPEC 2013 report detailing conditions in Corehole #18, the main aquifer intersection occurred at 1,490 ft (bgs) in the Oriskany Sandstone, with the base of water reasonably be expected to be at, or above, the base of the Bertie Group.

In the RESPEC 2013 report, no information was given as to the nature of the porosity and permeability distribution in the aquifer (intergranular or fracture?). This is because at the level of the main aquifer intersection samples were being collected as drill cuttings, not whole core.

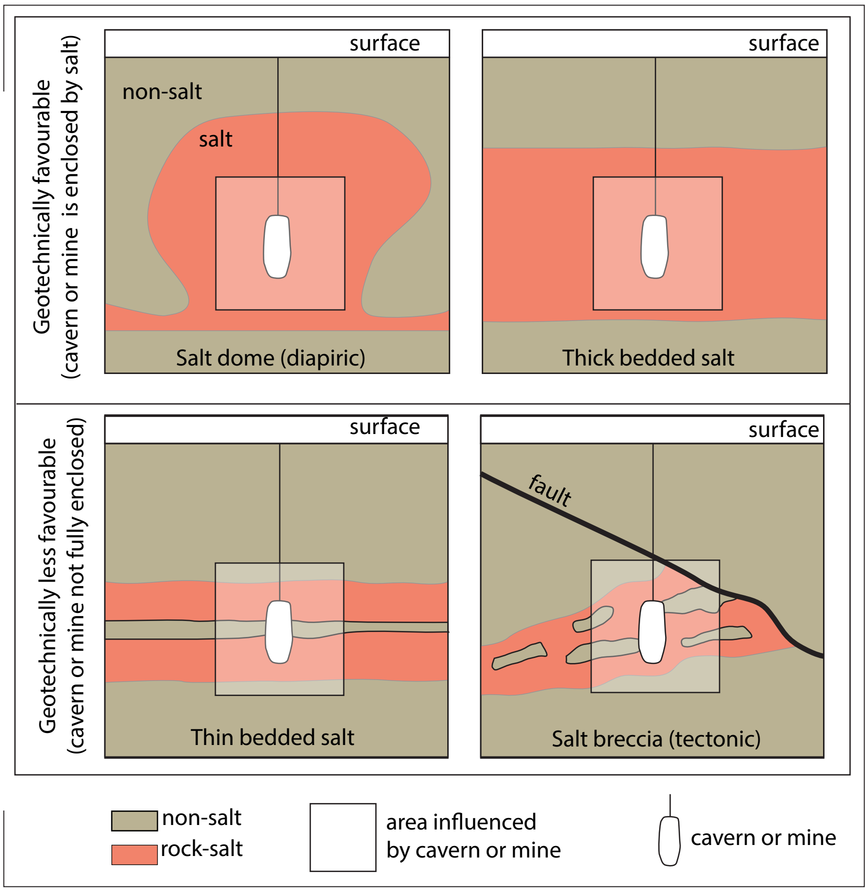

Figure 20. Schematic summarising geotechnically favourable and less favourable scenarios for mines and storage caverns in salt (after Gillhaus, 2010; Warren in press). The figure is not to scale. Ideally, a storage cavity or mine working should not intersect a salt anomaly and be located well away from the edge of a salt unit or any pen.etrative aquifer system in the target salt system.

If the undersaturated water in the main aquifer is held in a homogenous bedded host typified by intergranular porosity, then the pump test already done to quantify entry rates and discussed in the CoreHole 18 report can probably be extrapolated reasonably well from pump measurements in a narrow borehole diameter (inches across) to a 14-foot wide shaft. If the aquifer is fractured, then flow rates and aquifer interconnectedness have not been reliably quantified in the Corehole. Unexpected water volumes may be encountered during upward reaming of Shaft #4.

The Cayuga Lake margin aquifer setup has many similarities to the aquifer system in the region above the former Retsof mine (Figure 15). A complete study of the nature of the hydrology in the region between the base of the Shaft #4 pilot hole and the current sub-lake mine working is needed before permission to construct Shaft #4 is granted. Likewise, possible positions of undocumented brine wells should be documented.

In addition to these concerns with the current set of available information, there is also the unknown but possibly substantial effect of storing a significant volume of halite-undersaturated water in the current mine workings. In the author's opinion, without more study, it is unwise to store what may be a significant (as yet unquantified) volume of reactive and penetrative water in a slurry capable of salt dissolution in an already mined portion of the mine (see Patience Lake case history).

Conclusions with recommendations

Joffe effects, in my opinion, may not drive or even broadly indicate regions with potentially significant salt mine stability problems (see Addendum 1 for detail on Joffe effects as documented in the Cayuga Salt Mine). Joffe effects tend to operate at near-homogenous intracrystal scales, as atmospheric moisture enters and leaves with the seasonal changes in the mine atmosphere. They are part and parcel of any salt mine operation, as are slightly changing rates of roof closure and salt heave. Rapid changes in roof closure rates are often registered only after collapse has initiated or even occurred.

What drives significant instability at times of salt mine expansion is the unexpected intersection of zones holding substantial halite-undersaturated pore water volumes located in or immediately out-of-salt. Worse yet, is the connection scenario when the intersected zones possess high potential inflow rates and are connected to large reservoirs of halite-undersaturated pore waters . This is especially so when such unexpected pore waters are connected to the mine workings via open fracture porosity

Further rock typing and hydrological information needs to be collected and technical considerations made of this data before permission to the construct Shaft #4 is granted. To date, the New York State authorities have not required of the mine operator appropriate technical data suitable to make a "best-practice" judgement on whether to grant permission to move forward with Shaft #4.

Before a firm decision is made, the following set of documentation and studies should be required of the mine operators.

1) What is the geological situation ("stay in the salt") in the areas where an unknown and possibly significant volume of halite-undersaturated water is to be stored? This is not the typical situation in water sumps in salt mines excavating bedded salt, although it has been done in thicker salt bodies in mines in some diapiric structures in eastern Europe.

If the proposed water storage area is such that the water volume is fully encased, and it will not weaken the strength of intervening salt pillars, or while stored, drive dissolution and connection with unexpected aquifers in adjacent "out-of -salt" positions, then such below-ground storage of pilot hole and shaft reaming inflows should be feasible.

2. What is the nature of the permeability and porosity in the aquifer level to be encountered at the Bertie-Oriskany levels during upward reaming. This interval was sampled via cuttings, not core, when Corehole #18 was drilled. At this stage, it is not known if the encountered aquifer poroperm is held in a homogeneous medium or held in a highly inhomogenous host, as is typical of a fractured aquifer reservoir. If it is held in a homogenous bedded host, then the pump test already done to quantify entry rates and discussed in the CoreHole 18 report can be extrapolated reasonably well from the narrow borehole diameter to a 14-foot wide shaft. If the aquifer is fractured, then flow rates and aquifer interconnectedness have not been reliably quantified by pump tests in a narrow borehole. Unexpected water volumes may be encountered during upward reaming of Shaft #4.

3. What do the salt textures captured in the core from Corehole #18 indicate in termsof possible acquifer proximity? The current description of salt textures in the RESPEC report does not define the nature of the various processes likely influencing the formation of various salt textures. Current salt sedimentology allows one to differentiate between tectonic, diagenetic and salt dissolution textures and breccias. Work on the publically-available core from the Himrod Mine shows all these textures are present in the salt layers in the Syracuse Fm; they are distinct and capable of being classified (e.g. Figures 18, 19 in Warren 2015).

Such a sedimentological study of the salt core in Corehole #18 would better refine the hydrological situation in the vicinity of Corehole #18 and if there is a possible hydrological connection already in existence between the top of salt and the overlying potential aquifers located in and above the Bertie Formation.

The further integration of the salt texture information derived from the core with the mineralogical information already measured in the wireline data run in Corehole #18 would help to refine such a hydrological model, which could then be tied back to the current understanding of the mine geology and improve the utility of predictive ore quality models.

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Addendum: How important is is short term humidity variation in terms of mine stability?

This section was added to the report on Shaft #4 as state authorities made an additional data request to the mine operator as to the possible influence of increased humidity on the measured Jolle effect and any observed increased closure rates tied to regions of current waste water ponding. In my opinion, observations of the Jolle effet are not relevant to predicting regions of the mine edges where possible unexpected aquifer influxes may occur.

The effect of humidity changes on rates of roof subsidence in the Cayuga Mine is normal and was documented and succinctly explained by van Sambeek (2012). Figure 21 summarises some of his relevant long-term closure measurements in the Cayuga Mine over a 23-year period in selected yield-pillar panels. During the period 1994 to 2003, monthly closure measurements plotted according to date of the year (Figure 21a). Obvious seasonality exists in the closure rate and, because of its long distance from the air intake shaft, this panel is buffered from temperature changes, so the seasonality is most likely caused by humidity changes (van Sambeek, 2012).

Another yield-pillar panel had room closure measurements made over five years (2006-2012), in conjunction with simultaneous temperature and humidity measurements (Figure 21b). The figure illustrates two types of normal salt relaxation and closure behaviour. When measurements started in 2006, the panel had been mined five years earlier, and it was inactive but still ventilated. As shown, the temperature was nearly constant, and the humidity varied with the seasons. The measured room-closure rate tracked the relative humidity.

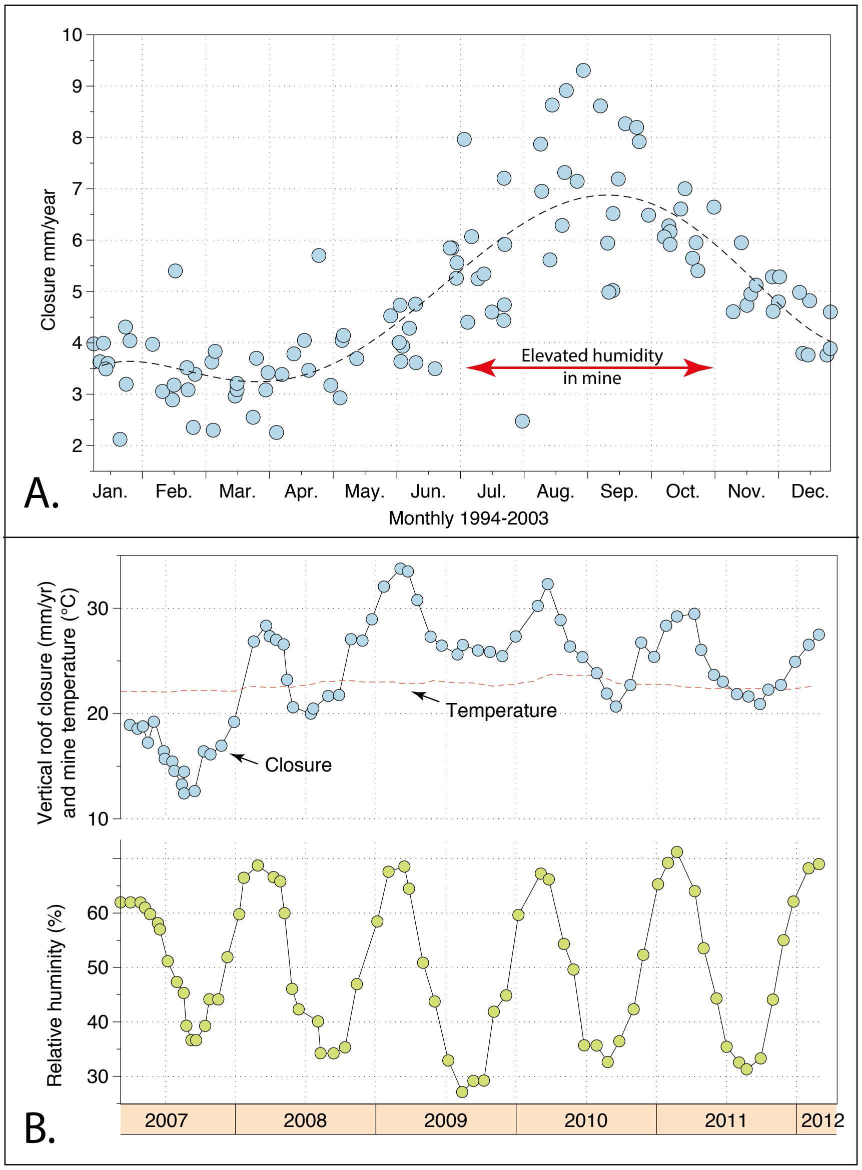

Figure 21. Closure rates in Cayuga Mine (replotted from Van Sambeek, 2012). A) Closure rates (mm/year) complied from monthly measurements across 1994-2003. B) Room closure rate (mm/yr), ambient temperature (°C) and relative humidity (%) at a long term closure station.

Then beginning in March 2007, backfilling of the panel began using the waste product from the underground mill (a mixture of rock particles and salt fines). The waste comes into the panel on a conveyor, is moistened to lessen dust and improve compaction, and then spread around using heavy diesel equipment. A combination of the seasonal humidity in the ventilation air, the water added, and water vapour in the diesel equipment exhaust pushed the humidity level in the panel above the previous maximum level of 60 percent. The relative humidity approached (but of course could not exceed) the nominal 75 percent critical humidity threshold for deliquescence of water vapour on salt. The annualised room-closure rate simultaneously increased with the greater humidity level. Moreover, since Figure 21b shows the temperature was nearly constant throughout this period (and there was no nearby mining), the closure rale changes are attributed to humidity changes.

Five complete annual cycles are shown in Figure 21b. The first cycle (mid-2006 to March 2007) occurred while the panel was inactive and quiet (before backfilling operations started). The later annual cycles (after March 2007) are measured during backfilling activities, so the room-closure rates are greater than their earlier values. The correlation trend is that closure during the humid months will be nominally 75 percent faster than during the drier months.

Van Sambeek (2012) concludes that humidity-enhanced salt creep (rightly or wrongly called the Joffe effect) has historically been considered a phenomenon mostly observed in laboratory tests on small test specimens that were probably in a state of dilation. The laboratory tests showing the most pronounced Joffe effect were unconfined and exposed to the atmospheric humidity changes, particularly greater humidity, although the phenomenon was reversible. In contrast, van Sambeek (2012) documented several examples of long-term in-mine deformation measurements showing an in situ change in rock-salt creep rates occurs as the seasonal humidity changes, thus proving the Joffe effect occurs even on a large scale. Additional extensometer measurements in both salt pillars and salt around a shaft show that the Joffe effect influences salt even at depths of several meters.