Implications of a comparison of geological and hydrological conditions in the Akzo-Retsof, Morton-Himrod and Cargill Cayuga salt mines, New York State

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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. This type of connection, in combination with unexpected structural complexity, leads to problems that can ultimately lead to loss of a salt mine via a combination of flooding and roof collapse.

In the author's opinion, comparisons between geological conditions at Retsof, Himrod and Cayuga salt mines, as detailed in this report, show that it is premature for the New York State Department of Environmental Conservation (NYSDEC) to grant permission for the expansion of the current Cayuga Mine workings northward, beyond the existing mining licenses. Nor should the construction of Shaft #4 at the Cayuga Mine be approved without further study of geological and hydrological conditions in the area between the proposed position of Shaft #4 and the current Cargill-Cayuga mine workings (see also comments in Warren 2016a). Two things should be done in the near future in order to accumulate sufficient data for a more informed set of decisions.

1. Additional evaluation of existing seismic data collected in the Lake Cayuga area: This will involve the re-evaluation of the public-domain raw seismic data from lake-parallel 2D lines, along with the integration of public domain well data to improve velocity profiles. The final processed data can then be interpreted, along with quantified error values, for the depth to basement and top of salt calculations

2 Re-evaluation of core collected in the Shaft # 4 stratigraphic well: Cores collected in the drilling of the Shaft #4 stratigraphic well should be examined for evidence of the extent of possible salt dissolution and alteration, using current understandings of the significance of evaporite textures.

Rationale 1

Salt geology 1

Three Mine Comparison 3

The Retsof Mine 3

Operational history of the Retsof Mine 3

Geology and hydrology of the Genesee Valley in the vicinity of the Retsof Mine collapse 5

Water influx tied to changes in room and pillar mining approach? 6

Loss of roof stability and flooding of the mine 7

Events indicating the loss of the mine 9

What caused the loss of the mine? 10

Morton-Himrod Salt Mine, Seneca Lake 10

Mine history 11

Geologic nature of salt at Himrod 12

Problems leading to mine shutdown and abandonment 15

Cargill-Cayuga Salt Mine 15

Operational history (Goodman et al., 2009) 15

Cayuga Geology 17

Potential problems with expansion to the north 18

Implications 19

Recommendations 20

1. Use of seismic data 20

2. Improved use of core data in the study of the Cayuga Salt 21

References 21

Rationale

In order to understand better the geological complexities that need to be dealt with as the Cayuga Salt Mine moves northward into increasing shallower salt, this report compares the geology, mining approaches and outcomes in the AKZO-Retsof, Morton-Himrod and Cargill-Cayuga salt mines. The aim is to quantify geological and hydrological similarities and differences. All three mines are conventional salt mines, utilising room and pillar extraction techniques and all operations are or were focused on extraction of salt from the Silurian Salina Group. All are located in New York State, but only the Cargill-Cayuga salt mine is still active. The report should be read in conjunction with Warren 2016a. The Akzo-Retsof and the Morton-Himrod mines are no longer active for reasons discussed in this report. The American Rock Salt mine is not included in this assessment as there is insufficient information in the public realm to make an evaluation.

Salt geology

Beds of Silurian salt in the Vernon and Syracuse formations of the Salina Group extend across the northeastern USA and Canada, from Michigan to the Appalachians, and from Ontario to Ohio (Figure 1a). Beneath New York State a number of these Salina Group salt beds are mined as a source of de-icing salt (Figure 1 b). Currently, there are two active conventional salt mines in New York State; one operated by Cargill Salt is located beneath Cayuga Lake, the other located near the town of Geneseo is operated by American Rock Salt. The Cayuga Lake salt mine is the much larger of the two mines. Silurian Salt is also solution-mined along the southwestern edge of Lake Seneca and the brine product used for salt manufacture and as a chemical feedstock.

The Silurian salt occurs in layers that dip southwards across much of the Finger Lakes region and becomes increasingly folded and faulted as one moves toward the Appalachian fold belt. From Lake Seneca eastward toward the Appalachians, the salt stratigraphy in the subsurface is typified by changes in salt layer thickness and continuity related to a combination of dissolution and increasing deformation. Thus, mines exploiting the Salina Group do not all extract salt from the salt unit (B-F in Figure 1b).

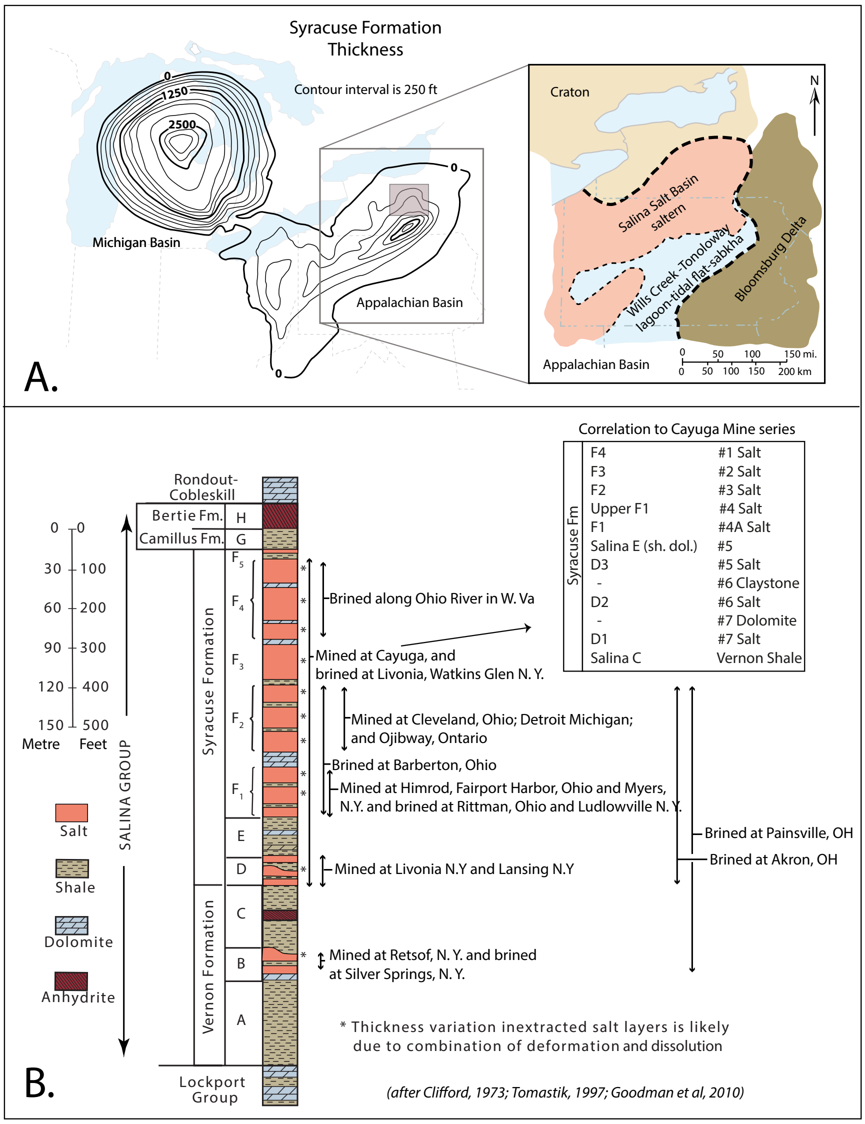


Figure 1. Extent and stratigraphy of salt the Siluria Salina Group in the northeast USA. A) Distribution and thickness of salt in the Salina Group. B.) Figure 5. Stratigraphy (rock unit names) used to describe salt units in New York State and surrounds, along with a listing of targeted salt intervals in former and current mining or brine well operations across the region.Insert gives the correlation of the regional stratigraphy to units used in the Cayuga Mine.

Name	Location	Company	Salt Type	Depth (ft)	Mined Height (ft)	Current situation
Cayuga	Ithaca, NY	Cargill	Deformed beds Silurian salt	2,300	13	Expansion and new shaft planned - active conventional
Whiskey Island	Cleveland, OH	Cargill	Bedded Silurian salt	1,850	28	Roof stability concerns ? - active conventional
Lyons	Lyons, KS	Lyons Salt	Bedded - Permian salt	< 1,000	16	Active conventional mine
Kanopolis	Kanopolis, KS	Independent Salt	Bedded - Permian salt	< 1,000	16	Active conventional mine
Hutchinson	Hutchinson, KS	Vaults and Storage	Bedded - Permian salt	1,000	16	Secure storage vaults in former salt mine
Detroit	Detroit, MI	Detroit Salt	Bedded Silurian salt	1,800	18	Active conventional mine
Fairport	Fairport, OH	Morton Salt	Bedded Silurian salt	1,850	13	Active conventional mine
Hampton's Corner	Geneseo, NY	American Rock Salt	Deformed beds Silurian salt?	1,100	15	Active conventional mine
Avery Island	Avery Island, LA	Cargill	Diapiric - Jurassic salt	Vertically deep deep with limited lateral extent	25-100	Active conventional mine
Weeks Island	Weeks Island, LA	Morton Salt	Diapiric - Jurassic salt		25-100	Active conventional mine
Cote Blanche	Cote Blanche Island, LA	Compass Minerals	Diapiric - Jurassic salt		25-100	Active conventional mine
Hockley	Hockley, TX	American Salt	Diapiric - Jurassic salt		25-100	Active conventional mine
Grand Saline	Grand Saline, TX	Morton Salt	Diapiric - Jurassic salt		25-100	Converted to salt solution operation

Table 1. Some of the current salt mines operating in the USA (extracted from SaltWorks® version 1.7 database)

What typifies this bedded Silurian salt target, across its extent, is a limited layer thickness compared to salt that is mined in diapiric salt features, as in the Five Islands region the US Gulf Coast (Table 1). This limited thickness also means the various Silurian salt units are interlayered with non-salt sediments, mostly shales, dolomites and limestones. Consequently, the salt tends to flow like putty between the non-salt layers. Salty intervals tend to flow, fold and thin, while non-salt interlayers tend to be more brittle and so fracture and brecciate. And so, mined Jurassic salt targets in diapir structures along the US Gulf Coast tend produce relatively pure ores form thicker targets, with inherent low levels of non-salt materials, while products from the salt beds exploited in the various salt mines of New York State tend to be less pure and contain blocks and stratiform clasts of non-salt lithologies. Such blocks of non-salt sediments, encased in salt that has flowed and dissolved are seen in the widespread brecciate bodies adjacent to salt ore in all the mined stratiform salt masses across New York State. The same set of properties explains the high levels of insoluble residues in the solution cavities in the Watkins Glen brine field at Lake Seneca.

Based on extensive subsurface observations, Goodman and Plumeau (2004) summarised the nature of the Silurian salt across New York State as follows: 1) Beneath the eastern Finger Lakes Region of New York, salt bed textures predominantly reflect tectonic shear; little evidence of true primary bedding appears to be preserved. 2) Tectonic signatures are still apparent in the Genesee Valley in New York based upon similar salt lithofacies to the eastern Finger Lakes Region and rock-in-salt features reported in the literature. 3) Tectonic signatures persist into northern Ohio, but primary depositional bedding in the form of halite-anhydrite rhythms becomes more apparent. 4) The regional decollement in the salt sequence that has been typically modelled as occurring at or near the base of the Salina F salt, actually is a multi-level phenomenon affecting the B salt, the D salt and the F salt zones. Instead of a single plane of slippage, each of the three major regional salt zones appears to have suffered deformation that varies locally in response to the lateral pinchout of specific salt beds. 5) Patterns of deformation in synjacent shales and dolomites suggests that "salt withdrawal basins" exist between regional anticlines in the Finger Lakes Region of New York. Roof rock above an observed withdrawal basin in one mine shows evidence of extensional deformation, whereas compressional deformational features are clearly evident in the same roof rock stratum 4 miles to the south beneath a regional anticline. 6) Zones of thick salt in New York do not necessarily record original depocenters. Thick F-salt zones in New York are dominated by folded, faulted and brecciated sequences. Non-salt strata have been observed in drill cores to be "standing on end", thus exaggerating the original thickness of the local section. Lateral lithofacies trends in the non-salt strata and lateral termination/gradation of halite-dominated intervals into anhydrite/shale sequences (eastern basin margin) and anhydrite/dolomite sequences (western basin margin) are the best means to interpret paleogeography.

Three Mine Comparison

Three salt mines in New York State (Akzo-Retsof; Morton-Himrod and Cargill-Cayuga) targeted salt from a set of salt units that are now folded and variably dissolved. All mines focus on extraction from widespread Silurian Group evaporite intervals and all mines are located beneath water-saturated Pleistocene glacial valley sediments. Hence, a geological and hydrological comparison between the three mine sites will aid in developing a better understanding of the likely geological situations that could be encountered as subsurface operations at Cargill-Cayuga salt mine move northward to exploit increasingly shallower salt and Shaft #4 is constructed to facilitated the northward shift of the mine workings.

The Retsof Mine

At the time it was operational, the 24 km^2 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 2, 3).

Operational history of the Retsof Mine

Retsof Mine started operating in 1885 after completion of the 3.7× 4.9-meter wide, 303.5-meter-deep Shaft #1. The mine claimed an initial 5,460-metric- tons per day hoist capacity (Goodman et al., 2009). Early main haulage ways were driven east and west while production headings were driven north (updip) for salt-tramming ease. Room heights in the 6-meter-thick salt bed were 2 to 4 meters, with salt left in both the floor and roof. The 4-meter-high rooms were worked in two benches. Rooms were 9.2 meters wide and separated by 9.2-meter pillars. At that time there was no timbering, the mine was dry, mine air temperature was 17°C, and the mine was largely gas-free.

By 1958, the Retsof Mine was connected to the former Sterling Mine for ventilation and emergency escape purposes [Figure 3a; Gowan et al., 1999]. By the late 1960s, the mine had advanced beneath the Genesee River and Valley (Figure 3b). By the early 1970s, the Retsof Mine operators had installed an underground surge bin, fed by a new conveyor system, and the rail haulage system was eliminated. Mainline conveyors led to yard or panel belts feeding each mining section, where a Stamler feeder-breaker crushed salt delivered by diesel-powered Joy shuttle cars. In the early 1980s, the shuttle cars were gradually replaced by load-haul-dump vehicles (LHDs). In 1969, Netherlands-based Akzo Corporation acquired International Salt Company and operated the Retsof mine until its abandonment due to flooding in 1995.

During April 1975, an explosion occurred in the original Sterling B Shaft during efforts to control water inflow into the Retsof Mine from this abandoned and partially collapsed shaft (Goodman et al. 2009). The leaky B Shaft had not been used or maintained for years. By 1975, International Salt was concerned that freshwater inflow from the B Shaft could pose a salt dissolution, collapse, and flooding risk to the then-connected Retsof Mine. Removal of a partial shaft blockage of timber and rock debris was attempted as a means of regaining airflow needed to safely access, rehabilitate, and grout off the water inflow to the shaft and mine below. A maintenance crew attempted to dislodge the shaft obstruction by pushing a large boulder into the shaft that was to drop down and knock through the debris. A methane explosion occurred upon impact. The upward force of the explosion killed four people on the surface near the shaft collar and injured others. On November 19, 1990, a roof fall resulted in two fatalities. Deformation and fracture of roof salt can occur because of a concentration of stresses; i.e., punching of the roof by stiff pillars. After the fatalities, the mine tested smaller, yielding pillars to alleviate roof falls (Figure 2). Positive test results led to the adoption of a yield-pillar design.

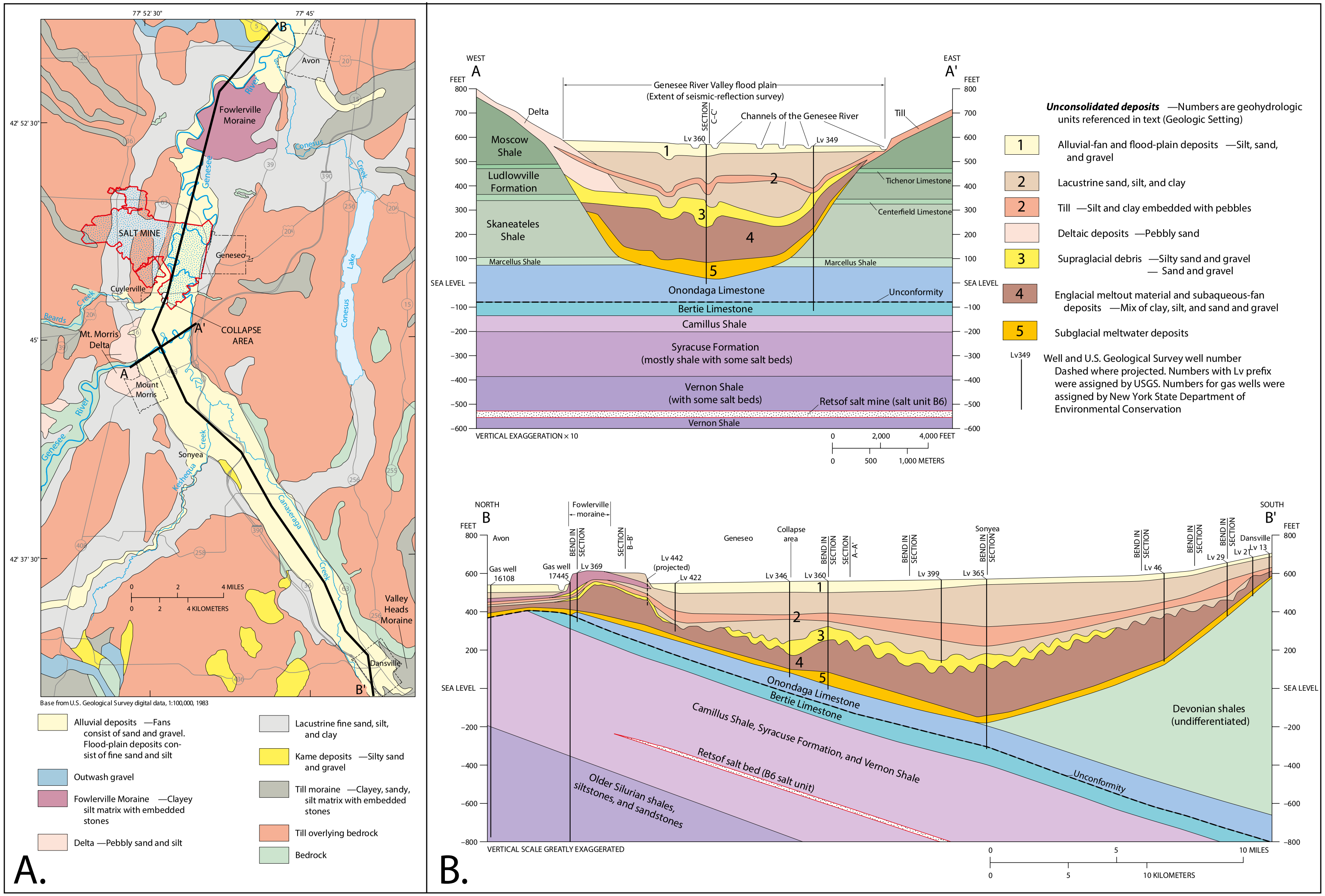


Figure 2. Geology of the Retsofs Mine, The Genesee Valley and surrounds. A) Surficial geology. B) Geological cross sections, also illustraing main Pleisotocen aquifers and aquitards (after Yager et al., 2013; Yager, 2001).

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 prior to 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.

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 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 2; Yager, 2001; Young and Burr, 2006). The Genesee Valley spans through 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 have been recorded in the Genesee River Valley (Figure 2); 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 1b, 2b). 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. As the glacier had scoured through the valley, carving out bedrock and accumulating sediment, steep-sided valley walls were cut and pro-glacial lakes formed. The glacial lake sediments are dominated by muds, but also include large boulders and cobbles carried to the lake depressions by glacial ice. Fluvial sediment from the Genesee River and Canaseraga Creek also drained into these glacial lakes. 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 (Figure 2). 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 of the surface and is variable in thickness throughout the valley, but normally ranges about fifty feet thick and is still being deposited across the Genesee River Valley floodplain (Yager, 2001).

The 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 bedrock valley walls. The uppermost aquifer consists of alluvial sediments 20 to 60 ft thick (unit 1 in Figure 2b); the middle aquifer consists of glaciofluvial sand and gravel less than 10 ft thick (unit 3 in Figure 2b); and the lower aquifer consists of glaciofluvial sand and gravel about 25 ft thick overlying the bedrock valley floor (unit 5 in Figure 2b). These aquifers are separated by aquitards dominated by muds and clays (Units 2 and 4 in Figure 2b).

The now abandoned Retsof Mine lies 550 to 600 ft below the eroded valley floor (Figure 2b). Hence, the upper and middle 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. The principal water-bearing zone in the bedrock overlying the mine consists of fractured carbonates and sands near the contact between the Onondaga and Bertie Limestones. The fractured aquifer that occurs at this level in the stratigraphy supplied a significant volume of the water that ultimately flooded the Retsof Mine. The glacial aquifers are hydraulically connected at the edges of the confining layers and in subcrop zones, 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, 2001). The hydraulic head distribution in the confined aquifers under natural (precollapse) 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 reservoired 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 Fowler-ville Moraine (Figure 2).

Water influx tied to changes in room and pillar mining approach?

In 1993, ceiling falls began to occur in rooms in the deepest part of the Retsof mine near its southern boundary (Figure 3a; Yager et al., 2009). In response, the mine owner, AkzoNobel Salt Incorporated (ANSI), turned to an innovative “yielding pillar” mining technique that utilised many narrow (20 feet × 20 feet) pillars rather than few wide ones in the mined section (Figure 3b). Geotechnical analyses indicated that the resulting configuration would allow the salt pillars to slowly yield and create a “stress envelope” in the surrounding bedrock to support the entire mined room.

Closure monitoring was conducted in the yield-pillar test panels and the two full-scale panels during mining to measure panel behaviour and to see if the new design mitigated the floor and roof problems being experienced in the large pillar area of the mine (van Sambeek et al., 2000). Monitoring initially indicated that room closure rates were slightly greater than expected, but had an overall character (trend) of steadily decreasing rates, which is consistent with stable conditions. This trend

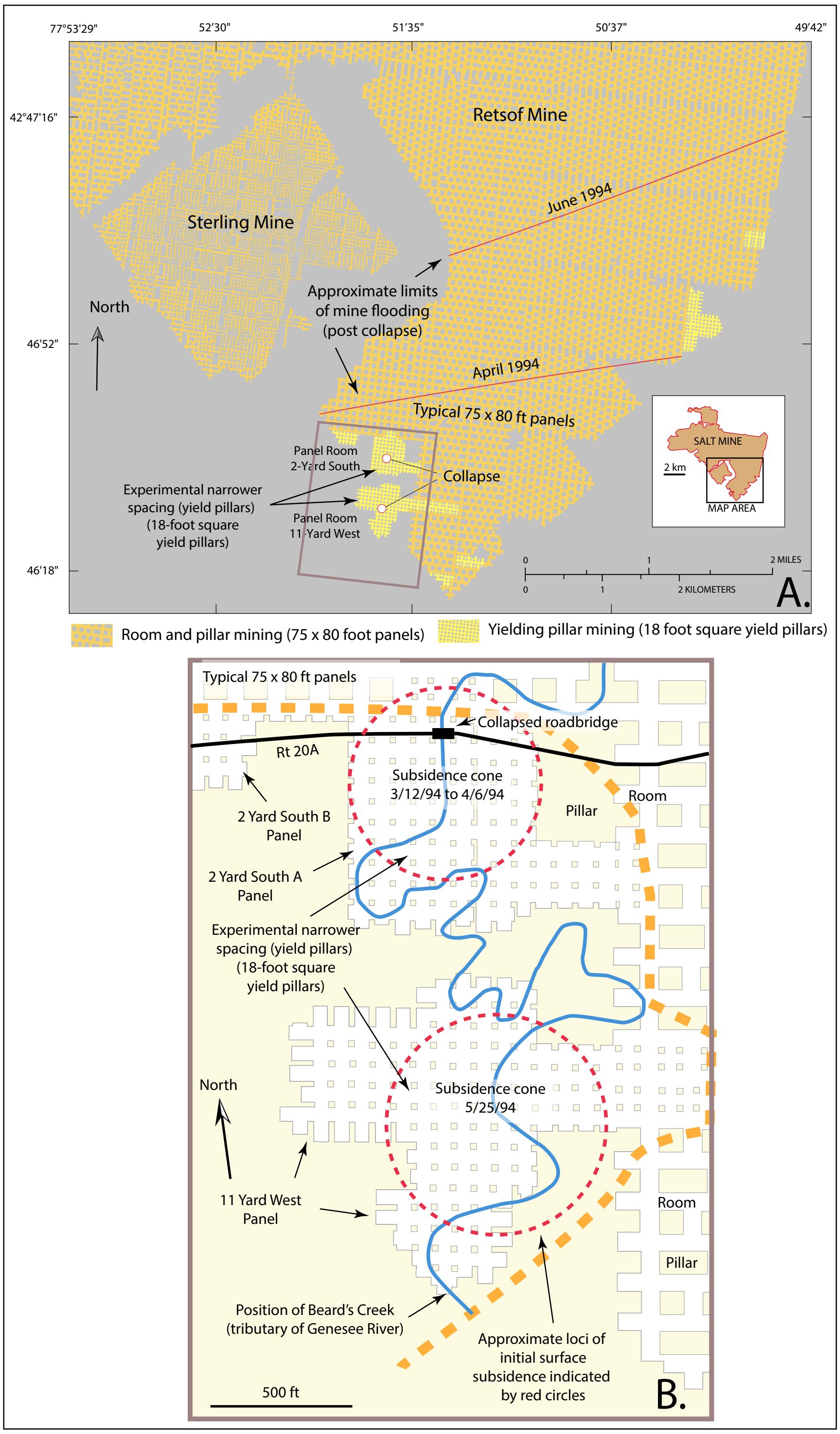


Figure 3. Retsof Mine. A) Room and pillar structure in the southern extent of the Retsof Mine at the time of the roof collapse and flood, also shows the position of the water flood edge after the collapse (after Yager et al., 2001). B) Detail of the new yield panel area and design at the time of collapse and its position relative to subsequent collapse features at the landsurface (after Nieto and Young, 1998; see also Figure 4).

changed dramatically to a rapid and unstable closure rates in the final weeks leading up to the inflow. The change in trend was initially obscured by fluctuating closure rates because salt extraction was occurring between the two yield-pillar panels as the monitored abutment pillar was isolated. Whereas the closure rates were expected to decrease after this mining was complete, they did not; in fact, they increased. This change in panel character later interpreted to indicate that a pressure surcharge existed or developed over two of the yield-pillar panels prior to the in- flow (Gowan et al., 1999).

Loss of roof stability and flooding of the mine

In November 1993, strain measurements in a yielding-pillar area within the mine indicated a larger than expected deformation of salt near the eastern wall of room 2 Yard South (Figure 3a, b). Mining in the area was halted as ceiling falls of salt continued during the next four months. On March 12, 1994, a magnitude 3.6 seismic event, caused by a large roof collapse, was detected by seismometers more than 300 miles away. Mine workers attempted to enter room 2 Yard South but found it was blocked by a pile of rock rubble within the formerly mined room and that saline water entering via fractures in the mine roof. Over the next several weeks, Akzo made concerted attempts to save the mine by pumping water out and drilling around the collapse area to inject cement grout so as to stabilise the collapsed room and prevent a further inflow of water. Meanwhile, unstable shale layers overlying room 2 Yard South sagged and collapsed to form a 300-foot-diameter zone of rock rubble that slowly propagated upward through overlying layers of shale (Figure 3b). This column of rock rubble is referred to as a rubble chimney.

The propagating rubble chimney eventually reached a layer of carbonate (limestone) rock that was strong enough to temporarily resist further collapse, stopping

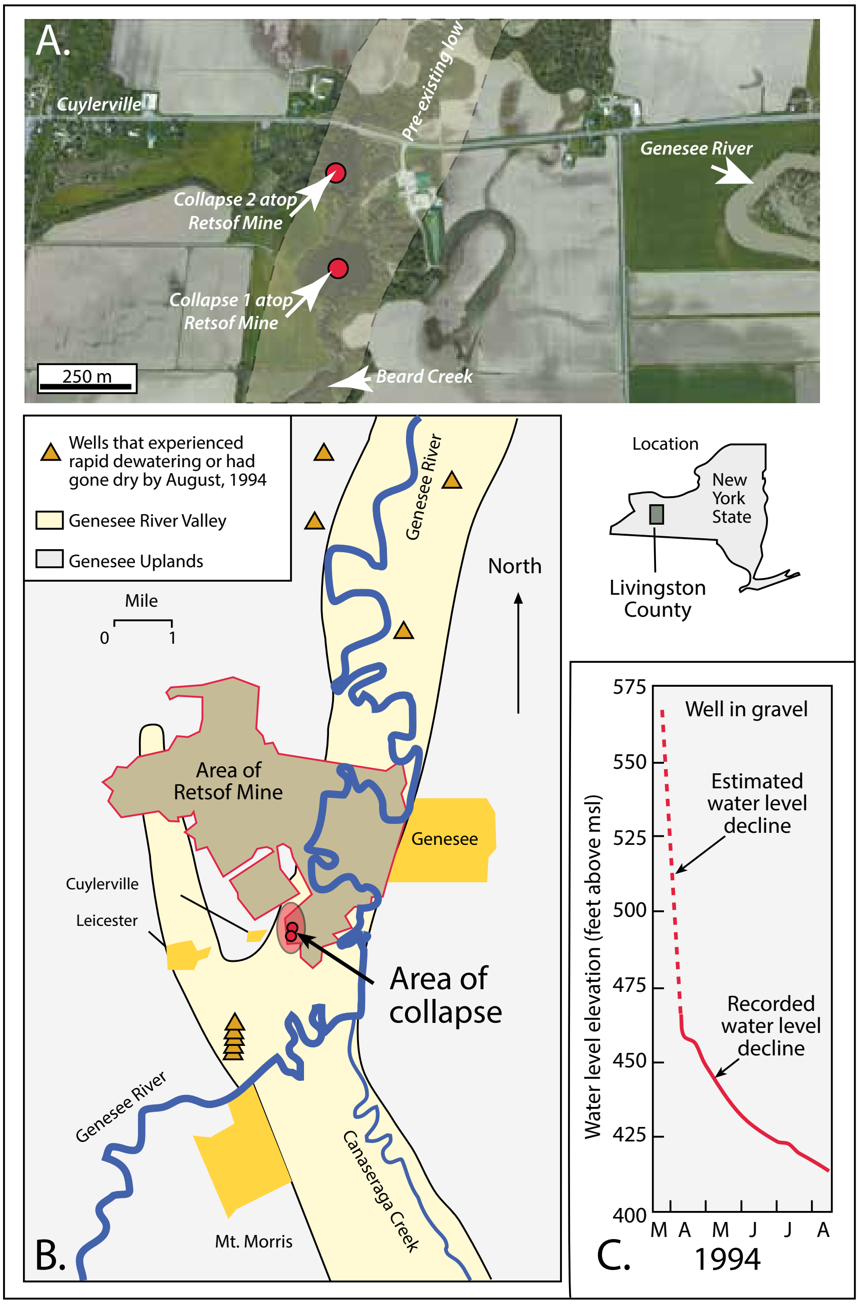


Figure 4. Retsof Mine collapse (after Warren 2016b). A) Location of the collapse dolines atop the former Retsof Mine to the east of the town of Cuylerville. The doline occupies a pre-existing low that had also captured Beard Creek (Bing® 2012 image mounted and scaled in MapInfo). B) Locality and areas of collapse with effects on the landscape, along with a hydrograph from a well showing lowered water table in the Genesee River Valley (March 12 to August 12, 1994; after Tepper et al., 1997).

Figure 5. Surface effects related to Retsof Mine roof collapse. A and B) Partially water-filled solution collapse dolines above the region of yield pillars in the Retsof Salt Mine. C& D Subsidence-related roadbed collapse on Route 20A (images downloaded from < http://www.rcsiweb.org/gallery.html> on Dec 6, 2016).

further the rubble chimney's upward progression. At this point, the flow of water into the mine stabilised at about 5,500 gallons per minute. Water entering the mine was saline and probably a mixture of saline water from the shale and a prominent fracture zone aquifer within the Onondaga and Bertie Limestones (Figures 3, 6). By the end of March 1994, tons of cement grout had been injected into the mine and the rubble chimney through nearly 30 boreholes drilled in the collapse area, but these efforts failed to stem the rate of water flowing into the mine and the inflow was becoming increasingly less saline.

On April 6, 1994, the limestone rock layer collapsed, and 550 feet of unconsolidated sediments in the Genesee River valley quickly slumped downward into the resulting cavity, forming a sinkhole at the land surface, more than 15 feet deep and several hundred feet across (Figure 5). The collapse of the limestone rock was like pulling the plug in a bathtub—it allowed groundwater from a fresh-water aquifer at the base of the unconsolidated glacial sediments (the lower confined aquifer; Figure 6) to drain downwards through the rubble chimney and into the mine. By mid-April, a second collapse occurred in an adjacent room (11 Yard West; Figure 3). On May 25, a drilling crew working above room 11 Yard West felt tremors and removed their drill rig, and themselves, just before this second sinkhole formed at the land surface. This one had a surface expression that was more than 50 feet deep and several hundred feet across (Figure 4a). The discharge from the aquifer through both rubble chimneys increased the flow of water into the mine to about 18,000 gallons per minute.

Water began to fill the southern end of the mine and then spread steadily northward, dissolving the bases of the salt pillars that supported the mine ceiling (Figure 3a). As the pillars gave way, the southern part of the mine began to collapse, causing the land surface above it to subside. The greatest subsidence (more than 15 feet) was beneath the two sinkholes, which altered the channel of Beards Creek, allowing surface water to fill the sinkholes. The surface water did not flow downward to the mine, however, because hundreds of feet of fine-grained sediments underlie the Genesee River valley. The instability also forced the closure of the U.S. Route 20A bridge over Beards Creek; the southern end of the bridge eventually subsided by 11 feet (Figure 5c, d). The bed of the Genesee River 1 mile north of the collapse areas subsided by as much as 5 feet and altered the pattern of sediment scour and deposition along a 1.5-mile reach downstream of Beards Creek

Events indicating the loss of the mine

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. It 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 3b) 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, 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 3). 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 3). 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.

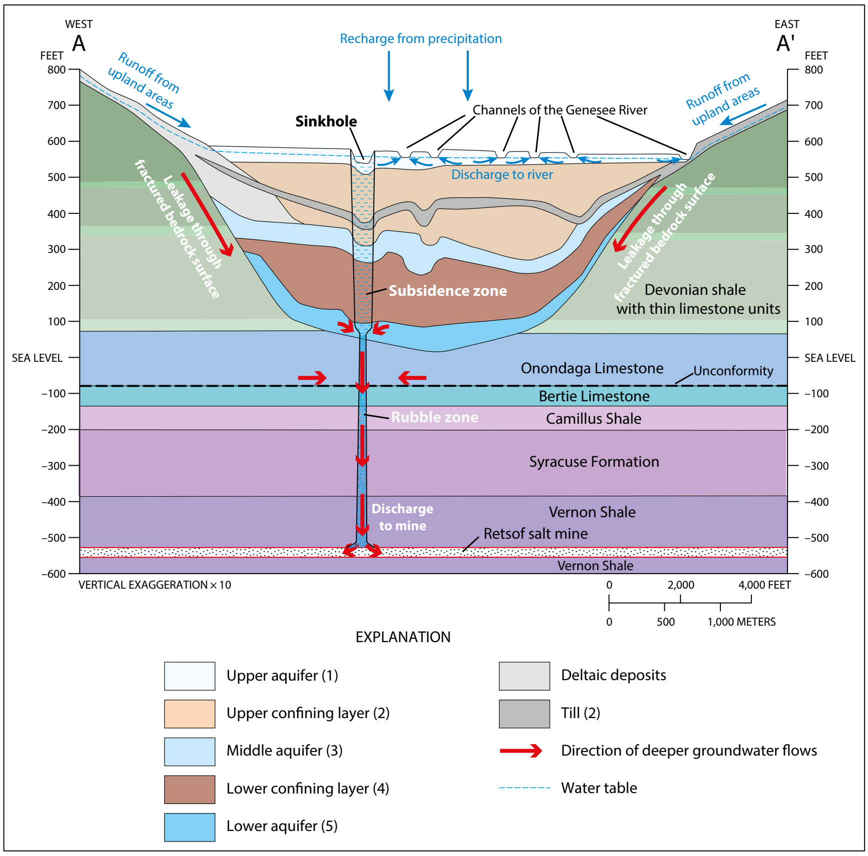


Figure 6. Stratigraphic section depicting rubble chimney above collapsed room in Retsof salt mine, Livingston County, N.Y. Also shown are the main aquifers that facilitated water influx into the flooding mine (inflow also drained natural and artificial brine-filled solution cavities in the stratigraphic levels above the working mine level (after Yager et al., 2009).

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; the fall in the water table as ground waters drained into the mine in effect meant some water wells went dry (Figure 4; 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 5. 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. Longer term adverse effects are mostly related to increasing salinization of the lower parts of the Genessee Valley aquifer system in the vicinity of the mine (Yager, 2013).

What caused the loss of the 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 the mine (Figure 4a). 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 greatly 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 history 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 Cayuga Mine region.

Morton-Himrod Salt Mine, Seneca Lake

The now abandoned Himrod mine is located to the immediate west of Lake Seneca and was constructed in the 1960s and early 70s near the town of Himrod to supply rocksalt to the Morton Salt Plant (Figure 7). The deepest part of the Morton Salt Himrod Mine is approximately 2050 feet (625 meters) deep.

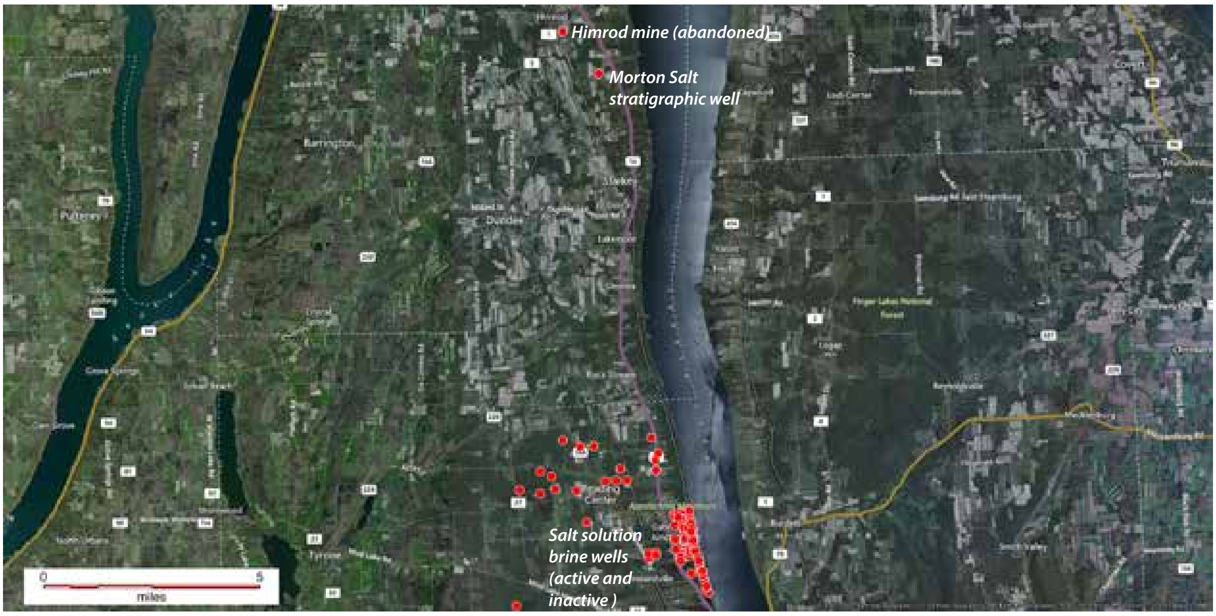


Figure 7. Location of the former Morton-Himrod Mine, the Morton Salt stratigraphic well, and various brine field and hydrocarbon wells to the south.

Mine history

Entrance to the mine was gained through two 18-foot concrete-lined shafts equipped with Koepe Hoists (Jacoby, 1977). The mine's two shafts were sunk by the Cementation Corporation of Canada (Goodman et al., 2009). When completed, the shafts were 2000 ft (610 meters) deep and overlain by 177 ft (54-meter) tall concrete towers containing the Koepe Hoists. Shafts were sunk by drilling and blasting methods and mucking was done by use of a Cryderman mucking machine. The device was about 10.7 meters long with a clam shell bucket at the end of a telescoping boom. Some strata penetrated during shaft construction yielded water, so the shaft was lined with concrete. Shaft liners were installed in 6.1-meter increments. Water supply for the plant was provided by a company-owned water system installed at Severne Point on Seneca Lake. Power to the plant site was backed up by diesel-powered generators. The mine's rail system, connected to the Penn-Central Railroad, accommodated 400 hopper cars. Mine ventilation was provided by two 300 hp fans at the surface.

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 (Figure 5). The extraction ratio when operational was around 50 percent (Goodman et al., 2009). With a 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 in nonmarketable fines termed F. C. salt, which was typified particulate matter of a size smaller than ten-mesh, with a 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.

Geologic nature of salt at Himrod

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 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 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 come from "within the salt" while Chute's and Jacoby's observations at Himrod include direct observations of the upper contact of the salt, a situation which the ongoing mine operations at Cayuga salt mine try hard to minimise ("stay in the salt"). 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 in all mines across the region, including Cargill-Cayuga

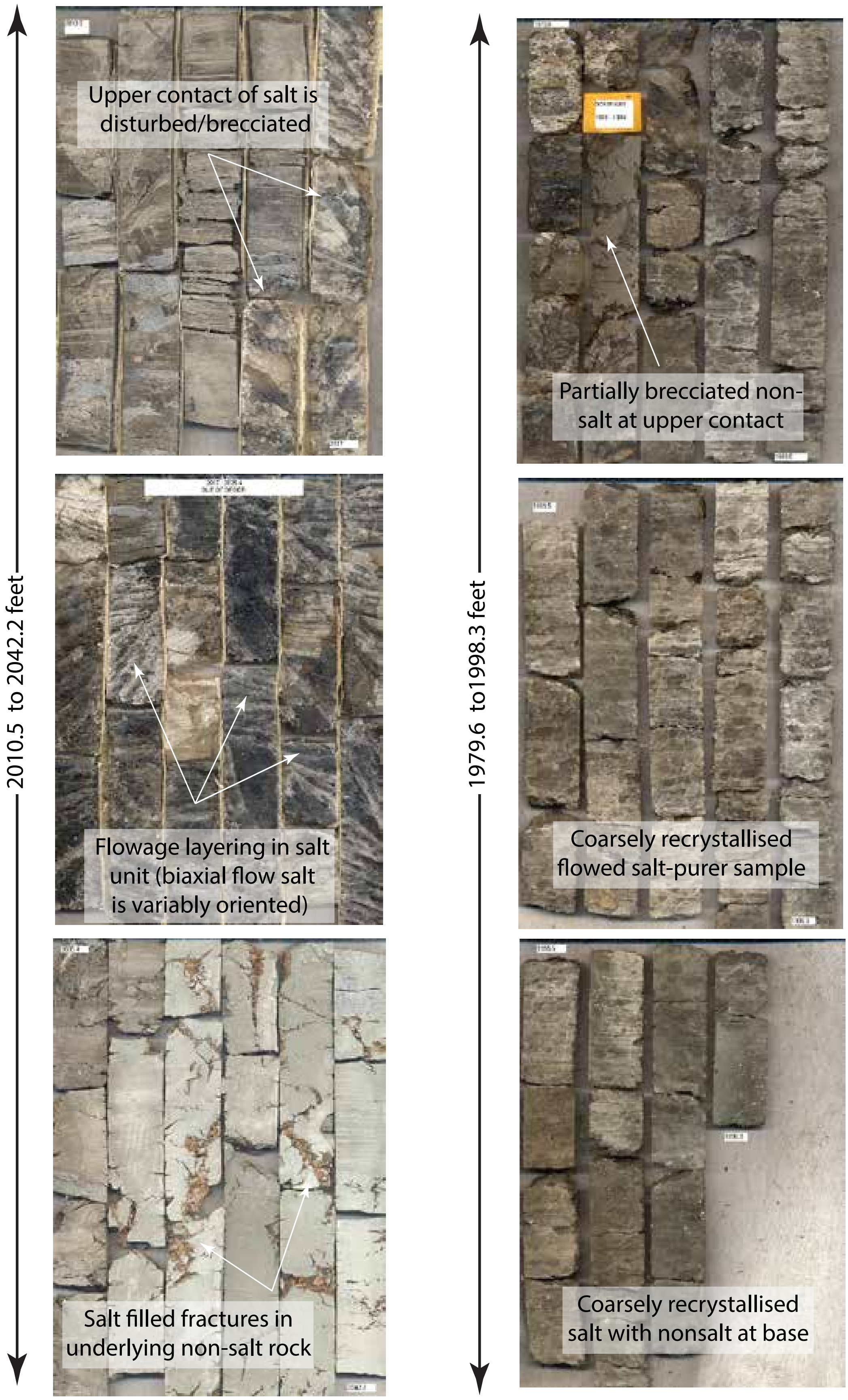
The stratigraphic well at Himrod is the Morton Salt Stratigraphic Core Test well (API 31-123-13174-00-00) and reasonable quality images of the various core trays are still available online (<http://esogis.nysm.nysed.gov/Cores_TOC.cfm>). Selected images of the various Salina Group salt units (B through D) intersected in this well are illustrated in Figures 8 and 9. Based on the author's experience (Warren, 2016b), all salt textures in these cores indicate that salt in the vicinity of the Morton-Himrod Mine has flowed, deformed and dissolved into 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 (Figure 9).

Likewise, the intrasalt beds in this well show evidence of widespread tectonic brecciation and fracturing. 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). 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.

The exact nature of the roof to the salt in the Himrod area and the presence of dissolved salt layers is also indicated by textures in the recovered core. First, there is a zone of poor core recovery (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 (Figure 9). 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 current salt layers, there are there are a number of 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 9). 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 supply the regional hydrology.

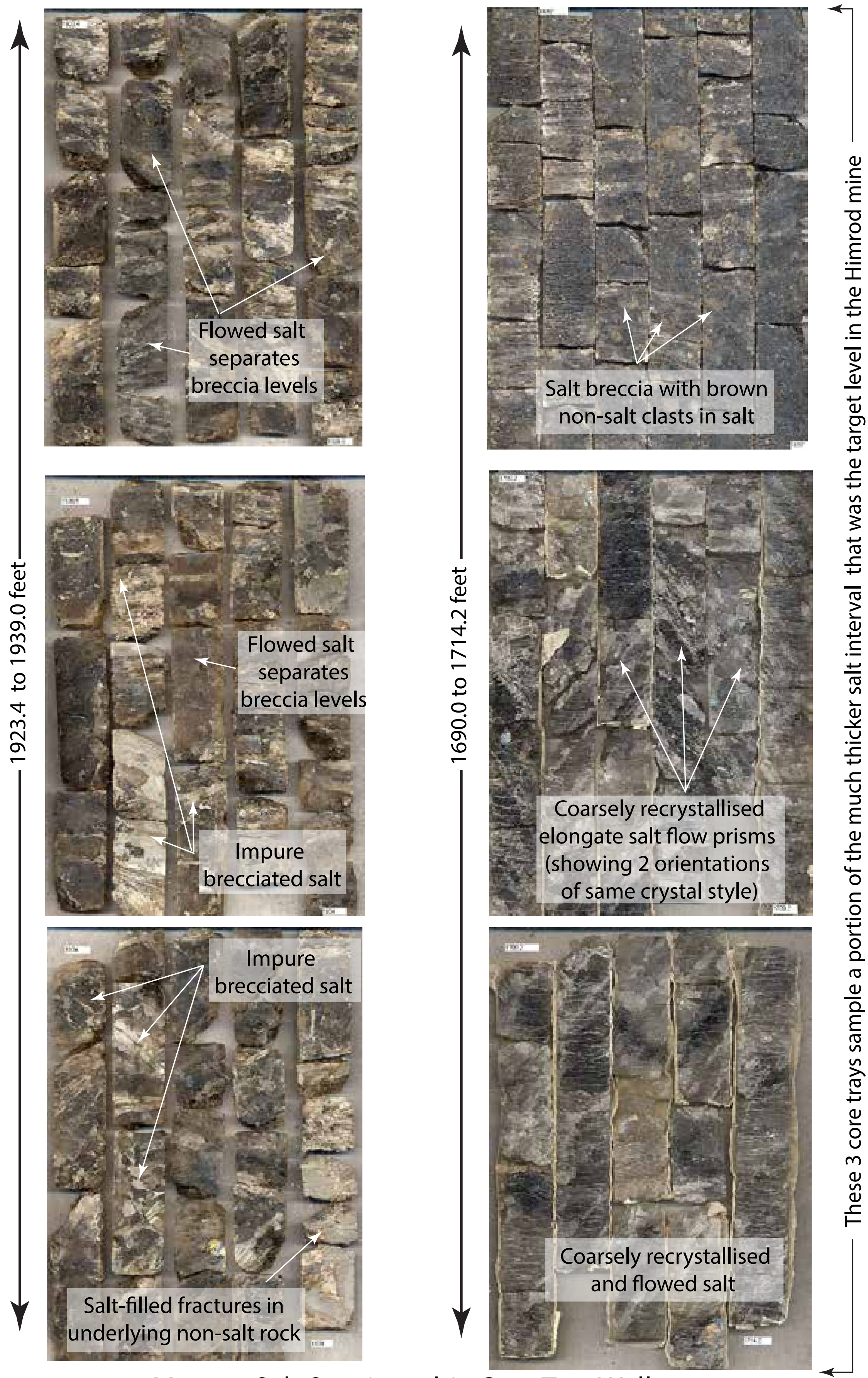
The importance of the textures in the cores illustrated in Figure 9 is that they show aquifer connection, so assumptions of isolation of the salt from fractured aquifers are likely not correct. These textures indicate that assumptions of no hydraulic connection between salt and fractured Palaeozoic aquifers are not correct.

As at Retsof and in the Cayuga Salt Mine, salt units in the Himrod- Seneca Lake region thicken and thin. Constant bed thickness is the exception, not the rule, when modelling salt in the Fingers Lake region. Internal and external sub-horizontallity of beds in and around the Salina Group salt units should not be assumed when modelling the layering in the salt-dominated sections across the region. Variable dissolution and the irregular thickness of the various salt units help explain why, once the Retsof mine workings were "out of the salt," water ingress to the mine was relatively rapid and why there



Morton Salt Stratigraphic Core Test Well
API 31-123-13174-00-00

Figure 8. Selected core tray photographs illustrating the deformed and brecciated nature of salt in the Himrod Mine area - Refer to Figure 7 for the position of this well and its location in relation to the Morton-Himrod mine and brinefields north of Watkins Glen. (Images downloaded from <http://esogis.nysm.nysed.gov/Cores_TOC.cfm>, last accessed Dec. 6, 2016)



Morton Salt Stratigraphic Core Test Well
API 31-123-13174-00-00

Figure 8., continued. Selected core tray photographs illustrating the deformed and brecciated nature of salt in the Himrod Mine area - Refer to Figure 7 for the position of this well and its location in relation to the Morton-Himrod mine and brinefields north of Watkins Glen. (Images downloaded from <http://esogis.nysm.nysed.gov/Cores_TOC.cfm>, last accessed Dec. 6, 2016).

Morton Salt Stratigraphic Core Test Well (API 31-123-13174-00-00)

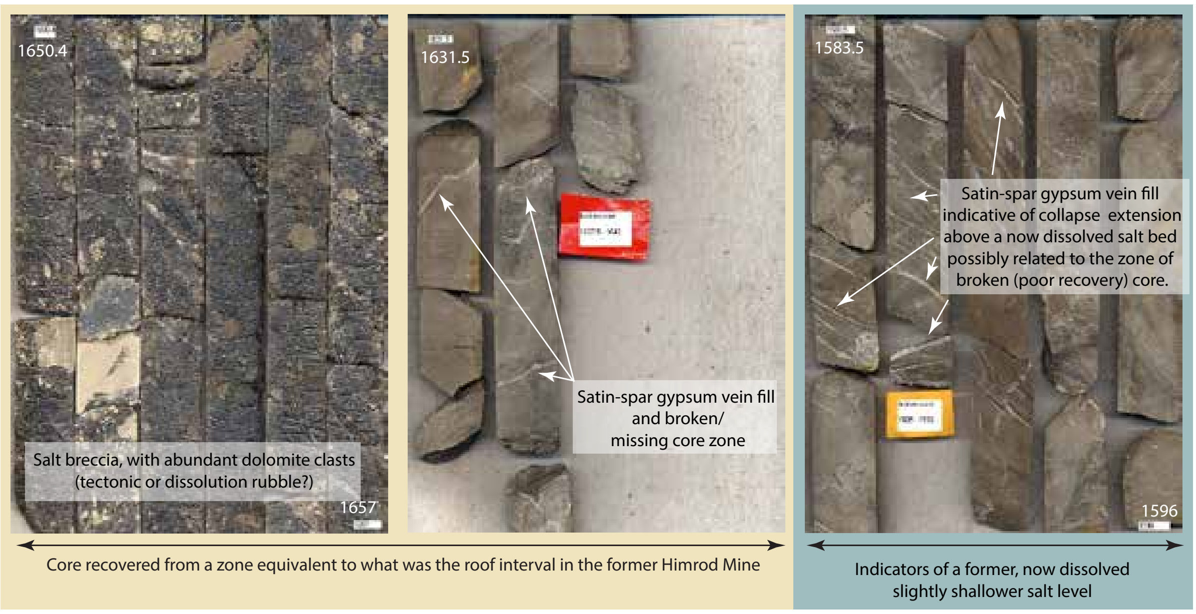


Figure 9. Rock-core based observations relevant to the nature of the top of a salt unit and indications of former, now dissolved salt levels in the Cayugan salt of the Salina Group. (Images downloaded from <http://esogis.nysm.nysed.gov/Cores_TOC.cfm>, last accessed Dec.,2016).

were ongoing problems with roof stability throughout the short operational life of the Morton-Himrod Mine.

Problems leading to mine shutdown and abandonment

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. According to Jacoby (1977), unstable roof conditions in the Himrod mine were primarily due to unexpected higher intensities of faulting and fracturing of the Salina Group sediments, as well as dissolution in the upper parts of the salt succession.

When the Himrod mine was active, there were constant concerns over unexpected roof falls (Jacoby, 1977) and in 1974 a Himrod miner was killed by an unexpected roof failure. Roof stability was an ongoing problem throughout the time the Himrod mine was active, and the Morton Salt Stratigraphic Well core helps with an understanding of why roof stabilisation was such a problem for the Himrod miners. The upper portion of this salt interval at Himrod is broken and brecciated, even though part of the target-ore salt horizon. Attaching roof bolts into this rock layer, rather than into a unit with more homogenous mechanical integrity, would have been an ongoing problem.

Cargill-Cayuga Salt Mine

The Cayuga Mine is the deeper and larger of two room-and-pillar salt mines presently operating in New York (Figure 10).

Operational history (Goodman et al., 2009)

The Cayuga Mine started operations in 1923 and has extracted salt from four different levels in the Syracuse Formation. The first production shaft was completed in 1918 at a depth of 451 meters to the shallowest (#1) salt bed. The surface plant was then completed, and mining began in January 1923. The highly variable, contorted nature of the #1 salt bed was soon discovered. In January 1924, the mine shut down, because the impure,

Figure 10. 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 kilometre. C) Approximate extent of current mine workings beneath Lake Cayuga and contour of base Salt #4; Image courtesy of Fractracker).

contorted salt could not be mined profitably. By June 1924, the Cayuga Rock Salt Company deepened the shaft to reach the relatively pure #4 salt bed level, some 587 meters below the surface (Figure 2). Mining restarted about 1927.

Again, as in Himrod and parts of the Retsof mines, the targeted salt bed was highly contorted, but the purity was high, and the miners were able to follow "rolls" (synclinal folds) where salt was thickest. The #4 salt bed was mined in an "open stope" manner (Figure 10c). Room widths and heights varied from 2.4 meters to 30 meters wide and 1.8 meters to 10.7 meters high. By 1927, undercutters were employed. The muck from the undercut and blasted salt faces was loaded onto cars pulled by a battery-powered locomotive.

The 1.2-meter-diameter #2 Shaft to the #4 bed was added around 1931 for ventilation and emergency egress. Salt was moved to the shaft bottom by rail, and skips hoisted salt to the surface. The skips dumped into a bin at the roof level of the surface mill building where salt was crushed and screened to size for various markets. In the 1930s, a diesel generator house was constructed to provide power for the mine; excess power was reportedly sold to the nearby community of Myers. The mine's #4 bed capacity gradually rose to 540,000 metric tons per year.

During the 1960s, core holes were drilled to the bottom of the Syracuse Formation in a successful search for deeper, undeformed salt beds. In 1968, Cayuga Rock Salt drove two slope tunnels down to the tabular, pure #6 salt bed at a depth of 702 meters below the surface. Mining in the extensive, relatively flat-lying nature of the #6 salt meant the mining approach was easily modernised.

Cargill Salt Division purchased the mine around 1970. The underground haulage system was changed from carts pulled by battery locomotives to front-end loaders feeding conveyor belts. An underground crushing and screening plant was built. By 1975, the production capacity increased to over 720,000 metric tons per year.

The Cayuga Mine presently has three shafts. The #1 Production Shaft has four compartments: two for skipping, one for an emergency cage, and one for a ladderway. The inside dimensions are 2.8 meters by 8.2 meters. The #2 Shaft was completed around 1931 as a 1.2-meter-diameter airway and escapeway. The #3 Shaft was drilled in 1975 and completed in 1976 at 3.4 meters inside diameter as an intake airway and service shaft, extending from the bottom of the 702-meter-deep #6 salt bed to surface.

The flat-lying nature of the #6 salt bed permits a regular room-and-pillar mine layout. From 1969 to 1976, the layout used 9.8-meter rooms on 36.6-meter centres, leaving 26.8-meter- square pillars. As at Retsof and Himrod, roof problems prompted experimentation with the "yield-pillar mine design." From 1976 to present, the mine has successfully used 4.6–6.1 meter square pillars and 9.2–12.8 meter wide rooms. Overall extraction is about 55 percent (Goodman et al., 2009).

In 1989, a surface conveyor belt and bin system replaced the old concrete "mill building" to improve efficiency. A new production headframe was added in 1991. By 1995, the mine was producing over 1,456,000 metric tons per year. A new underground screen plant was commissioned in 1995. German Salzgitter Maschinenbau AG "SMAG" equipment was then introduced and allowed different blasting techniques, which, combined with the SMAG equipment reliability, increased crew production by 40 percent.

In 2001, a compactor was added to the screen plant that converted up to 27 metric tons per hour of waste salt "fines" back into saleable-sized particles. Additionally, the "scoops" that dig and haul the blasted salt to the crusher were replaced by larger capacity, reliable "Elphinstone" models thereby allowing a 40 percent reduction in the original fleet of loaders, while achieving higher production. Today, the mine is capable of producing over 2,093,000 metric tons per year, which is shipped to more than 1,500 locations throughout the northeast United State. Twelve mining machines are operated by remote wireless control.

The mine operates via conventional salt extraction from four levels in the Syracuse Formation that encompassed the D and F units (Figure 1b; Goodman and Plumeau, 2004a, b). Today operations are focused on the D level salt. Currently, the mine extends some 7 miles under Cayuga Lake with six main tunnels in the mine for ventilation, transportation and haulage. Operations below Cayuga Lake create an advantageous situation in terms of "staying in the salt" compared to mines in areas of former brinefield operations, such as the former Akzo-Retsof mine.

Cayuga Geology

The geology of the Cayuga Mine is documented in detail in Prucha (1968). He found that most of the salt in the Cayuga mine was not distributed as preserved depositional thicknesses but that the salt layers, along with interbedded dolomites and shales, were caught up in regional deformation (folding and faulting) processes. This changed the thickness of the D and F salt units (Figures 11a, 11b, 12). Based on work in and around the mine he found that the Firtree Point anticline is a composite feature with second- and third-order sized folds superimposed upon the major structure (Figures 11b, 12). Numerous small-scale doubly-plunging disharmonic folds with amplitudes up to 30 m and wave lengths up to 100 m revealed a progressive change in the mode of deformation, from flexural-slip folding controlled by competent dolomite beds, to passive folding controlled by the much weaker rheological properties of the salt (Figure 12).

The change in deformation mode followed obliteration of the structural integrity and competence of dolomite interbeds, which failed on extension fractures, formed when individual flexural-slip folds reached a critical radius of curvature. This has created excursions from the predicted consistent thickness of the various salt layers and in places breaks up the continuity of the intrasalt dolomites and shales, so that they evolve into salt-encased breccias. The resulting varying thickness of salt layers, as seen in the Cayuga Mine, is illustrated on the mine scale for the eastern section of the mine in Figure 11a (Prucha 1968). In some places this lateral variation in thickness is controlled by stacking of the salt and its intrabeds into fault–thrust repeated salt units, these are somewhat thicker than predicted by the undeformed salt thickness (Jacoby 1969). In other places, the same salt layer was squeezed to where it is no longer present and brecciated beds of what were once nonsalt layers separated by salt have come into

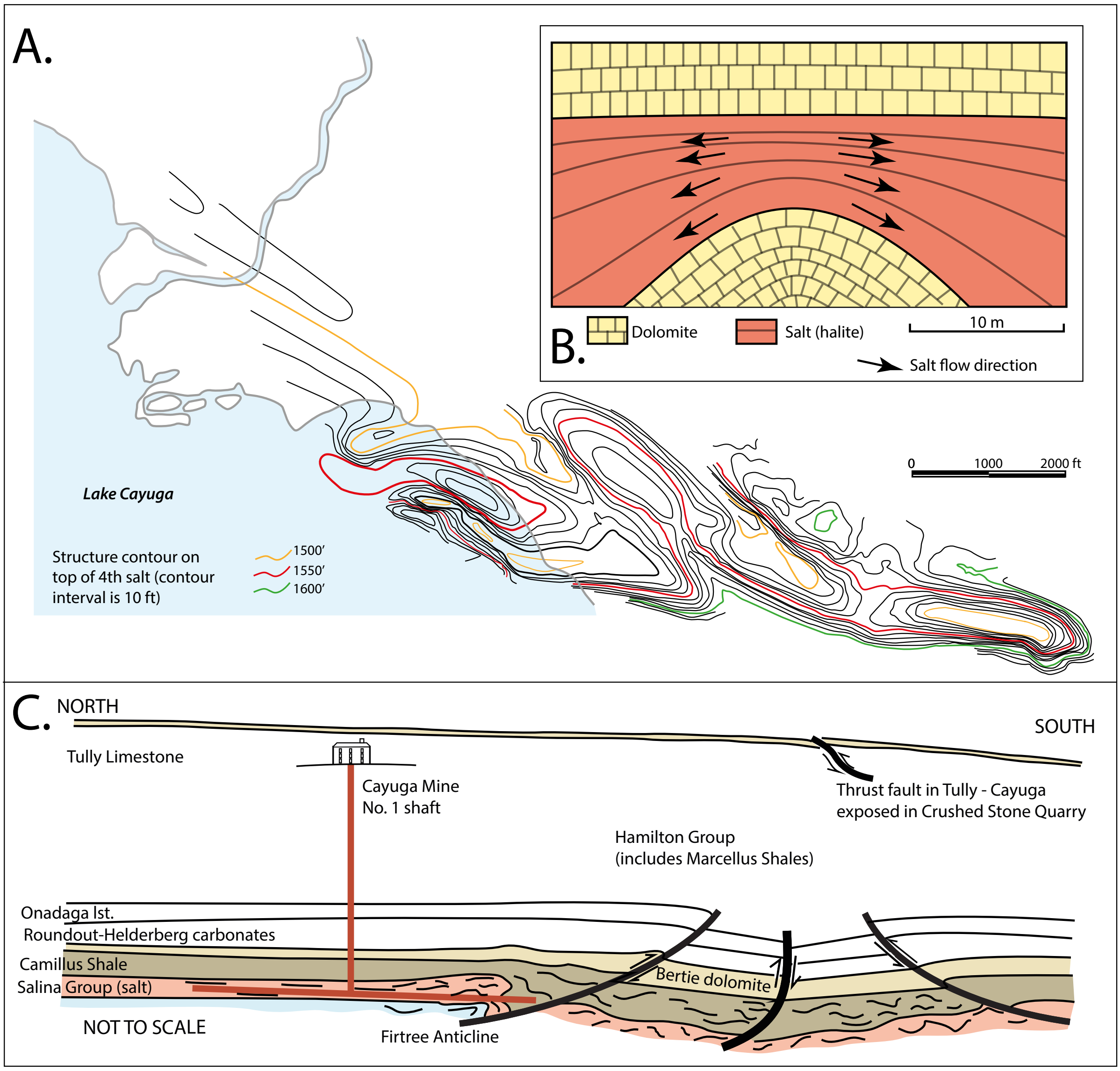


Figure 11. Salt geology in the vicinity of the Cargill-Cayuga mine. A) Structure contour (in feet) on top of the "4th" salt, this is top D in the current terminology. B) Illustration of the ability of salt to flow, while adjacent interbeds do not, so illustrating one mechanism for lateral changes in salt thickness. C) Interpretive schematic based on regional thickness changes seen in wells and observations in the Cayuga Mine (after Prucha, 1969; Goodman and Plumeau, 2004a, b)

direct contact. This style of intrasalt deformation within the thicker salt beds means that regionally one cannot assume a laterally continuous subhorizontal layering in the intrasalt dolomite and shale beds.

Potential problems with expansion to the north

Prucha (1968) found that the salt distribution in the Cayuga mine was not as flat-bedded depositional units but that the salt layers, along with interbedded dolomites and shales, were caught up in regional deformation (folding and faulting) processes, which had changed the thickness of the D and F salt units and brecciated parts of the stratigraphy (Figure 11). Based on work in and around the mine he found that the Firtree Point anticline is a composite feature with second- and third-order sized folds superimposed upon the major structure (Figures 11c). Numerous small-scale doubly-plunging disharmonic folds with amplitudes up to 30 m and wave lengths up to 100 m revealed a progressive change in the mode of deformation, from flexural-slip folding controlled by competent dolomite beds, to passive folding controlled by the much weaker rheological properties of the salt.

The change in strain intensity was associated with changes in structural integrity and competence of dolomite interbeds, which failed via extensional fractures, formed when individual flexural-slip folds reached a critical radius of curvature. This deformation created excursions from the predicted consistent thickness of the various

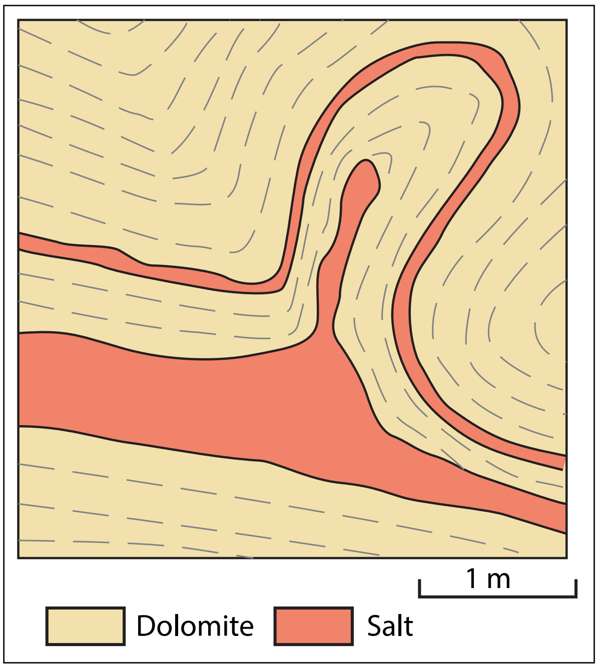


Figure 12. Field sketch of the geology visible in a mine wall showing clearly that the distribution of non-salt beds in the rocksalt is clearly not horizontal (after Prucha, 1968)

salt layers and in places breaks up the continuity of the intrasalt dolomites and shales, so that they evolve into salt-encased breccias, similar to those sample in the cores from the Morton-Himrod region. In some places this lateral variation in thickness is controlled by stacking of the salt and its intrabeds into fault–thrust repeated salt units, these are somewhat thicker than predicted by the undeformed salt thickness (Jacoby 1969). In other places, the same salt layer was squeezed to where it is no longer present and brecciated beds of what were once nonsalt layers separated by salt have come into direct contact.

This style of intrasalt deformation within the thicker salt beds means that regionally as the Cayuga Mine progresses north, one cannot assume a laterally continuous subhorizontal layering in the intrasalt dolomite and shale beds. When salt beds are targeted for solution mining, as in the brine field north of Watkins Glen, this is not a problem as the rubble from folded beds and salt breccias merely falls to the floor of the cavern as the salt is dissolved and cavern expands. However, when any assumption of salt bed continuity and thickness is made in planning and expansion of a conventional mine, it needs to be quantified. One way to do this is via the application of seismic techniques (discussed later).

Implications

A comparison of geology and developmental histories across the three mines offers a number of commonalities and suggests geological features that need to be better quantified before State Authorities approve ongoing plans for Cargill-Cayuga Salt Mine expansion. The most significant observations are summarised in Table 2.

All three mines are located in aligned glacial valleys filled with significant thicknesses (>200m) of layered Pleistocene glacial sediment. This glacial fill is unconsolidated and made up of alternating layers of sands and gravels acting as aquifers and finer grained sediments acting as aquitards. Because the sediment is unconsolidated if a salt collapse chimney ever makes its way from a mine level to the base of the fill this sediment will be subject to collapse. Solution chimneys will form above the breach and stope toward the landsurface. Water will then drain into and flood the mine level via the chimneys and feeder fractures, as evidenced by the loss of the Retsof Mine. In the deeper downcut portions of the Cayuga Valley, as in the glacially-cut valleys beneath Seneca Lake and the Genesee River, the thickness of the glacial fill and the degree to which glacial ice has eroded and downcut into the Salina Group is not well quantified. In the Cayuga Valley thickness to base Pleistocene above the current and future positions of the mine could be better quan-

Feature	Retsof	Himrod	Cayuga
Variation in thickness and continuity of targeted salt	yes	yes	yes
Thick overlying Pleistocene valley aquifers	yes	yes	yes
Poorly quantified sediment thicknesses to base of Pleistocene valley fill	yes	yes	yes
Brecciated, fractured and karstified aquifer at or near the level of the Bertie Formation	yes	yes	yes
Mine operators had expectations of predictable salt geology	yes	yes	Yes
Initial dry mine stage, with later brine ingress in older parts of mine	yes	mine life too short to judge	yes
Roof stability problems with consequent fatalies	yes	yes	no

Table 2. Commonalities across the three mines (see text for detail)

tified by re-interpretation of existing or newly collected seismic information (see later).

The loss of the Retsof mine and instability of the roof in the Himrod mine was in part a response to an influx of undersaturated brine from a regional fractured aquifer, located at the level of the Bertie Formation (Figure 6). This same aquifer overlies the working levels of the Cayuga Salt Mine. It will be intersected during the construction of the proposed Shaft #4. In the author's opinion, the hydrology associated with this likely fractured regional aquifer was not adequately quantified by the pumping testing done during the drilling of the shaft #4 test well (see Warren 2016a for detail). Better quantification of aquifer properties should be done before the construction of Cayuga Shaft #4 is approved, especially if the shaft is to be constructed using a Raise-Boring (upward-reaming) method of shaft construction. If unexpected high inflows are encountered when the rising Shaft #4 intersects the Bertie aquifer level, in many ways this situation could create an inflow hydrology scenario similar to that in the Retsof Mine, which ultimately led to the flooding of that mine.

Roof stability problems have been encountered in the expansion of all three mines and ultimately led to the abandonment of the Retsof and Himrod mines. In the case of the Cayuga Mine, roof stability problems were encountered in the older eastern portion of the mine, but were ameliorated by the expansion of the mine workings into the more stratiform level #6 salt, which dominates below the southern part of Lake Cayuga.

Key to the ongoing safe expansion of the Cayuga Mine northward is the notion that the expanding mine "stay in the salt" (Warren, 2016a,b). Problematic transitions "out of salt," with associated dissolution and loss of mechanical integrity, explain the hydrological and structural conditions that ultimately led to the loss of the Retsof and Himrod mines.

The operators of the Retsof Mine had experienced a long history of stable, predictable conditions in the mine workings and the loss of the mine over a period of two years was totally unexpected. One of the factors in the ultimate loss of the mine was likely to proximity and connection of the Retsof workings to the old now-abandoned Sterling Mine works. The age and lack of maintenance of the Sterling mine tunnels and shafts meant they had become both gassy and wet. Once workings were interconnected between Retsof and Sterling, this created problems for the Retsof operations. Age of a salt mine is always a problem as over time an increasing ingress of undersaturated waters will degrade the operating conditions in any salt mine. This is particularly true if access shafts to a mine are unlined (see Warren 2016b; Chapter 13).

Recommendations

In the author's opinion, comparisons between geological conditions at Retsof, Himrod and Cayuga, as detailed in this report, show it is premature for the New York State Department of Environmental Conservation (NYSDEC) to grant permission for the expansion of the current mine workings northward beyond the existing licenses. Nor should the construction of Shaft #4 be approved without further study of geological and hydrological conditions in the area between the proposed position of Shaft #4 and the current mine workings (see also comments in Warren 2016a). Two things should be done in the near future in order to accumulate sufficient data for a more informed set of decisions.

1. Use of seismic data

In order to evaluate the possibility of improving our understanding of Pleistocene sediment thicknesses across the Lake Cayuga Valley and the degree of underlying salt disturbance, the author of this report utilised a set of publications that summarise shallow seismic run over Lake Cayuga (Mullins and Hinchey, 1986; Mullins et al., 1996). These publications and downloaded data from a more recent set of publically available SEG-Y seismic files were sent to Mr Angus Ferguson to compile a preliminary interpretation and recommendations. Mr Ferguson is a seismic interpreter and seismic processer, with more than thirty years of international seismic experience in the oil industry. Mr Ferguson has also conducted geological research on the Onondaga Escarpment and so is familiar with the relevant geology in the Lake Cayuga region.

His initial comments and recommendations are given below (italicised). Time limitations mean Mr Ferguson is still working on a full in-depth interpretation of the available Lake Cayuga seismic data.

"…. Comments on Mullin's publications - agree with your concern for reliable depth to bedrock and depth to the top of salt:

The Mullins study uses an assumed velocity to convert to depth- there will be an error in this as the lowest glacial unit may have a different velocity from the above units due to the coarser grained sediments.

The imaging of the deepest part of the V-shaped floor to the lakefill and glacial sediments will be inaccurate due to reflections off the steep bedrock walls. This will also be a problem with the 2D data shot along the lakes where sideswipe will make the bedrock look shallower than the real depth.

There may be areas where erosion has down cut into the bedrock deeper than the overall measurement due to areas of bedrock weakness and fracture.

The 2D along-lake-lines data need to have the seismic velocities re-examined as they are critical to calculating the depth to top of salt. The data needs to be interpreted carefully due to the problem of sideswipe artifacts that will occur.

For the next stage of study I suggest:

Re-evaluation of the supplied raw seismic data from the lake-parallel 2D lines. The final re-processed data can then be interpreted, along with error values, for the depth to basement and top of salt calculations.

There needs to be an examination for potential areas where the bedrock has been downcut, and the interval between top of bedrock and top of salt has been reduced.

If there is any public-domain gravity data available, it may be useful to identify zones of thinned bedrock over salt.

The Mullins data needs to be merged with the supplied 2D parallel-to-lakes lines to make sure interpretations are consistent.

The exact location of the 2D lines needs to be checked as the supplied SEGY data did not state the co-ordinate system used."

2. Improved use of core data in the study of the Cayuga Salt

The operators of the Morton-Himrod mine encountered "unexpected" problems with respect to roof instability and ore quality. However, the Morton Stratigraphic Well was drilled in the in the early 70s, and we can now see in public domain core images that these cores contain textural indicators of the likelihood of both problems (Figure 8 and 9). The significance of such textural indicators was not recognised at the time that the cores were logged. In the early 1970s, there was little or no understanding of the multistage evolution of salt textures. Today these salt cores would be interpreted within a paradigm of ongoing textural and dissolutional re-equilibration known to overprint in all subsurface salt bodies, both stratiform and halokinetic (Warren 2016b). It is highly recommended that the cores and cuttings collected during the recent drilling of the Shaft #4 stratigraphic well be examined for evidence of the extent of possible salt dissolution, using current understandings of the significance of evaporite textures.

References

Chute, N. E., 1972, Subsurface stratigraphy and structure near the Morton Salt Company's Mine on Seneca Lake, New York: Geol. Soc. America Absts. with Programs, v. 4, no. 1, p. 9-10.

Clifford, T. J., 1973, Silurian rock salt of Ohio: Ohio Division of Geological Survey; Report of Investigations, v. 90, 42p.

Dumas, M., 1980, For $3 million In damages — Salt mine's neighbors file suit: Finger Lakes Times Part Two, January 31, 1980, provided by the Yates County Historian, Penn Yan, NY.

Goodman, W. M., D. J. Gnage, and P. H. Smith, 2010, Historical Review of Early Salt Manufacturing From Natural Salines in New York State: Implications for Present Day Challenges: Solution Mining Research Institute Spring Meeting, Grand Junction, CO, April 25–28, 30 p.

Goodman, W. M., and D. B. Plumeau, 2004a, Appalachian Basin Salt in the Silurian Salina Group: The View from the Mines: Solution Mining Research Institute Spring Meeting, Wichita, KS, April 18–21, 32 p.

Goodman, W. M., and D. B. Plumeau, 2004b, Appalachian Basin Salt in the Silurian Salina Group: The view from the mines: Northeastern Section (39th Annual) and Southeastern Section (53rd Annual) Joint Meeting (March 25–27, 2004) Paper No 70-4, Geological Society of America Abstracts with Programs, Vol. 36, No. 2, p. 145.

Goodman, W. M., D. B. Plumeau, J. O. Voigt, and D. J. Gnage, 2009, The History of Room and Pillar Salt Mines in New York State," in S. Zuoliang, ed., Proceedings, 9th International Symposium on Salt, Beijing, China, September 4–6, 2009, v. 2, Gold Wall Press, Beijing, China, p. 1239–1248.

Gowan, S. W., and S. M. Trader, 2000, The mechanism of sinkhole formation above the collapse of a small yield-pillar panel in the Retsof salt mine: In Proc. S.M.R.I. Fall Meeting Technical Session, San Antonio, p. 313-328.

Gowan, S. W., and S. M. Trader, 2003, Mechanism of Sinkhole Formation in Glacial Sediments above the Retsof Salt Mine, Western New York: Oklahoma Geological Survey Circular, v. 109, p. 321-336.

Gowan, S. W., L. L. Van Sambeek, and S. M. Trader, 1999, The Discovery of an Apparent Brine Pool Associated With Anomalous Closure Patterns and the Eventual Failure of the Retsof Salt Mine: Proceedings, October 1999 Meeting of the Solution Mining Research Institute, Washington, D.C., U.S.A.

Jacoby, C. H., 1977, Scoping report for Union Carbide on various salt mines in the United States, p. 52.

Mullins, H. T., and E. J. Hinchey, 1989, Erosion and infill of New York Finger Lakes: Implications for Laurentide ice sheet deglaciation: Geology, v. 17, p. 622-625.

Mullins, H. T., E. J. Hinchey, R. W. Wellner, D. B. Stephens, W. Anderson, T. R. Dwyer, and A. C. Hine, 1996, Seismic stratigraphy of the Finger Lakes: A continental record of Heinrich event H-l and Laurentide ice sheet instability, in H. T. Mullins, and N. Eyles, eds., Subsurface geologic investigations of New York Finger Lakes: Implications for Late Quaternary déglaciation and Environmental change: Boulder Colorado, Geological Society of America Special Paper, v. 331, p. 1-35.

Nieto, A., and R. A. Young, 1998, Retsof Salt Mine Collapse and Aquifer Dewatering, Genesee Valley, Livingston County , NY, in J. Borchers, ed., Poland Symposium Volume: Land Subsidence, Spec. Pub. 8, Assoc. Engineering Geologists, p. 309-325.

Prucha, J. J., 1968, Salt deformation and decollement in the Firtree Point anticline of Central New York: Tectonophysics, v. 6, p. 273-299.

Tepper, D. H., W. H. Kappel, T. S. Miller, and J. H. Williams, 1997, Hydrogeologic effects of flooding in the partially collapsed Retsof salt mine, Livingston County, New York: US Geol. Survey Open File Report, v. 97-47, p. 36-37.

Thompson, P. R., 2007, Morton Salt: Himrod Plant Has Interesting History: Newspaper article published in The Observer, Wednesday, July 11.

Tomastik, T. E., 1997, The sedimentology of the Bass Islands and Salina Groups in Ohio and its effect on salt-solution mining and underground storage, USA: Carbonates and Evaporites, v. 12, p. 236-253.

Van Sambeek, L. L., S. W. Gowan, and K. A. Payment, 2000, Loss of the Retsof Mine: Engineering Analysis: Proceedings, 8th World Salt Symposium, The Hague, The Netherlands, May 7–11, R. M. Geertman (ed.), Elsevier Science Publishers B.V., Amsterdam, The Netherlands, pp. 411–416.

Warren, J. K., 2016a, Technical requirements needed to approve construction of Shaft #4 in the Cayuga Salt Mine, New York State, Saltwork Consultants Report, 27 p.

Warren, J. K., 2016b, Evaporites: A compendium (ISBN 978-3-319-13511-3) Released Feb. 2016: Berlin, Springer, 1854 p.

Yager, R. M., 2013, Environmental Consequences of the Retsof Salt Mine Roof Collapse, US Geological Survey Open File Report 2013–1174, 10 p.

Yager, R. M., T. S. Miller, and W. M. Kappel, 2001, Simulated effects of 1994 salt-mine collapse on ground-water flow and land subsidence in a glacial aquifer system, Livingston County, New York: US Geological Survey Professional Paper, p. 1-80.

Yager, R. M., P. E. Misut, C. D. Langevin, and D. L. Parkhurst, 2009, Brine Migration from a Flooded Salt Mine in the Genesee Valley, Livingston County, New York: Geochemical Modeling and Simulation of Variable-Density Flow, USGS Professional Paper 1767, 59 p.

Young, R. A., and G. S. Burr, 2006, Middle Wisconsin glaciation in the Genesee Valley, NY: A stratigraphic record contemporaneous with Heinrich Event, H4: Geomorphology, v. 75, p. 226-247.