W1B: GEOLOGY, HYDROGEOLOGY, AND REMEDIATION OF THE ENVIRONMENTAL IMPACTS ASSOCIATED WITH THE RETSOF MINE COLLAPSE, CUYLERVILLE, NEW YORK

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ABSTRACT

The Retsof Mine in Livingston County, New York had completely filled with saturated brine by 1996 following a collapse on March 12, 1994 and subsequent flooding with ground water. Monitoring revealed salinity was increasing in the fractured rock above the mine in the collapse area, and it was connected to the upward rise of brine from the mine. A remedial plan was developed in 2003 to prevent the saline water and brine from entering the overlying aquifer system at the base of the glacial valley. The remedial plan consisted of pumping brine from the fractured bedrock in the collapse zone at a rate equal to the calculated brine squeeze rate from mine closure. The remedial plan was designed based on data collected from well drilling, geophysical logging, ground water sampling and analysis, geochemical modeling, and subsidence monitoring. Caliper and gamma-ray geophysical logging were employed to confirm the location of significant stratigraphic contacts, to refine the monitoring program. Caliper and acoustic televiewer logging were used to locate and evaluate the extent of fracture zones in the bedrock to determine the optimal placement of the pumps in the brine remediation wells. The remedial pumping program was initiated in May of 2006, after a period of pre-pumping monitoring, and was continued until December of 2013. Monitoring continued after cessation of pumping until November of 2014. The monitoring shows that the pumping program was successful in controlling the brine migration. The subsidence and geochemical modeling results show that no differential subsidence was induced by pumping induced dissolution of anhydrate and halite. The subsidence data also show that the brine squeeze rate is approximately 15.7 gpm, which is much lower than initially projected and that it would take 2,240 years for full mine closure at this rate. Approximately 47 percent of the mine area is at a closure rate of zero; consequently, it is likely that the overall mine closure rate will approach zero in the distant future.

Figure 1. Site Location Map

INTRODUCTION

The Retsof Mine in Livingston County, New York (Figure 1) collapsed on March 12, 1994 and began to flood with ground water. The mine was completely filled with saturated brine by 1996. The collapse occurred when the roof fell within two panels of small yield pillars located near the southern, downdip extremity of the mine (panels 2YS and 11YW) (Gowan et al, 1999; Gowan and Trader, 2000). Sinkholes formed at the land surface after the support for the underlying bedrock and glacial sediments was eroded by the influx of fresh water into the mine (Gowan and Trader, 2003). Brine began rising through rubblized zones in the bedrock above the collapse panels as the mine began gradually closing under the weight of the overlying rock and glacial deposits

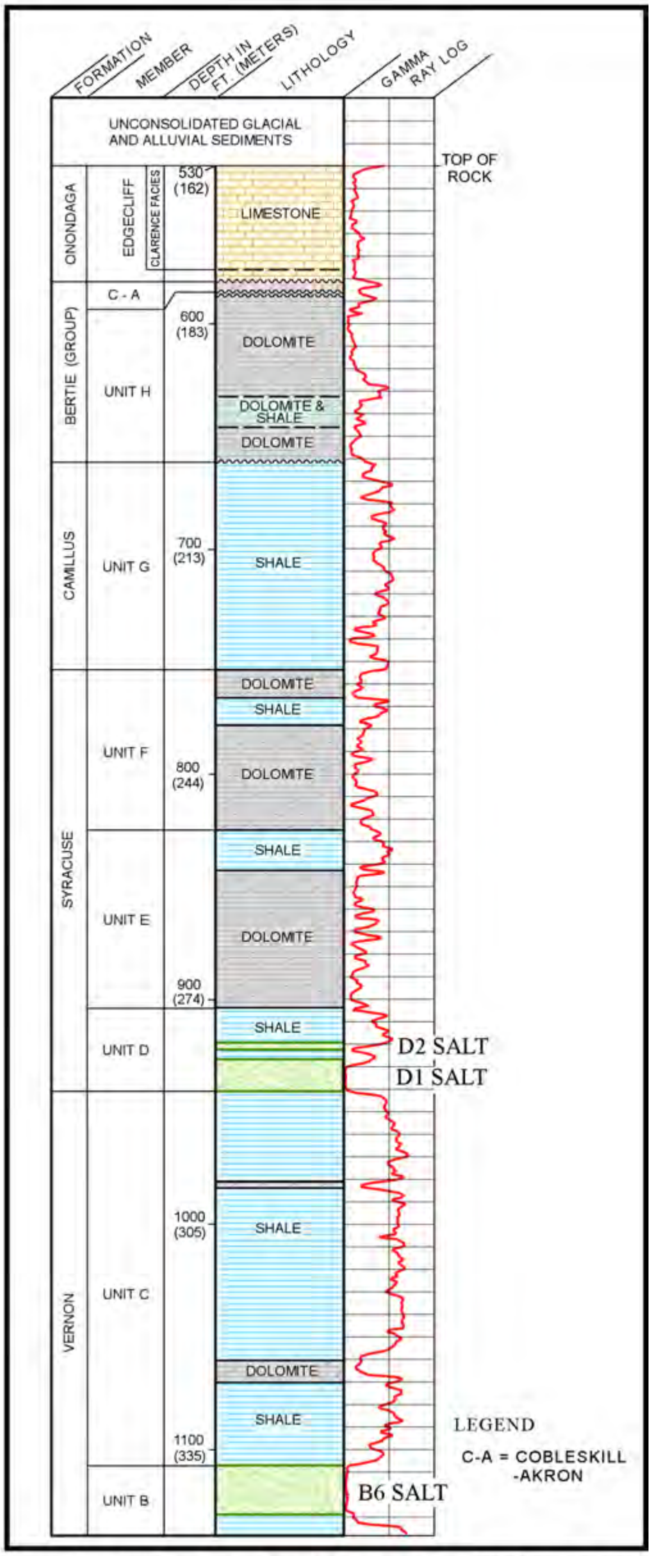

Figure 2. Detailed stratigraphic section for the Retsof Mine area with approximate formation depths for the collapse area.

A ground water monitoring program was initiated in 1996 to monitor the rising brine. This monitoring program revealed that elevated concentrations of brine were approaching the top of rock and entering the unconsolidated glacial aquifer system by 2003. These elevated concentrations triggered a legal agreement between New York State and the mine owner to protect the natural resources contained within the aquifer system from brine contamination. A remedial plan was designed to remove brine from the collapse zone by pumping from deep bedrock wells at a rate equivalent to the mine closure rate. It was anticipated that this balanced removal rate would simultaneously stop the brine from rising while preventing less saline water from being drawn into the salt horizons where further salt dissolution could occur and result in associated surface subsidence.

The remedial plan was an integrated system of subsurface monitoring, brine pumping, and brine disposal by on-site desalination. The development of these elements of the plan required the application of various subsurface investigation and data analysis techniques that included: geophysical logging of monitoring well and pumping well boreholes, ground water sampling and analysis, geochemical modeling, and subsidence monitoring. The objective of this paper is to describe the application and findings from the various sampling and analysis approaches, describe the remedial system, and summarize the results of the monitoring and remediation project.

Hydrogeologic Setting

The 11.2 square-mile Retsof Mine lies within the 20 feet (ft) thick B6 salt bed of Unit B of the Vernon Formation. The mine within the area of the collapse is approximately 1,100 ft beneath the surface and is overlain by 600 ft of

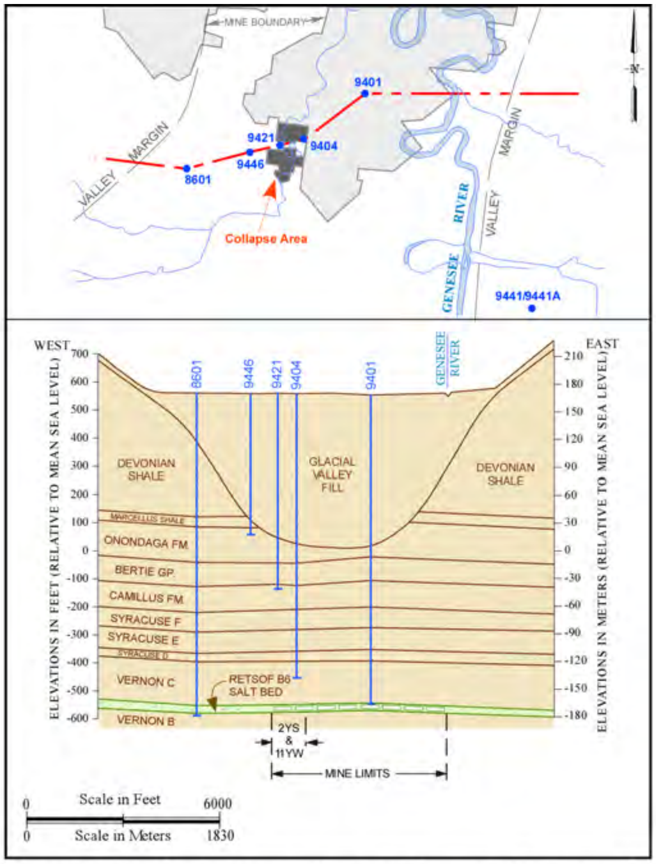

Figure 3. Geologic Cross Section Through Collapse Area Under Panel 2YS and 11YW.

dolostone, limestone and shale (Figure 2) and approximately 500 ft of glacial and alluvial deposits (Figure 3). The dolostone and shale layers of Unit C of the Vernon Formation and Unit D of the Syracuse Formation occupy the 190 ft of strata immediately above mine level and contain lenses and beds of salt and anhydrite (Gowan et al, 2006).

The B-6 salt bed dips southward at an angle of 0.65°. The updip extent of the mined section of the B-6 is at an approximate elevation of -273 ft below mean sea level (bmsl), and the bed at the collapse area is at an approximate elevation of -555 ft bmsl (Figure 4). Mining was progressing southward when the collapse occurred near the downdip limit of the mine (Figure 3).

Mining was conducted using a room and pillar method that extracted approximately 12 ft of the 20-ft bed and left between 35 to 40 percent of the salt as pillars. Ground water from overlying aquifers entered the mine through the collapse zone (Figure 5), dissolved salt, and filled the mine by 1996 with approximately 18 billion gallons of 100 percent saturated brine. The overlying aquifers that contributed to the mine inflow included the pre-existing brine pool in Unit D of the Syracuse Formation (Gowan et al, 1999; Gowan and Trader, 2000), the regional fracture zone at the Onondaga/Bertie contact (Bertie aquifer), the fractured zone at the top of the Onondaga Formation, and the glacial aquifer system at the base of the valley fill. The fracture zone at the top of rock combined with the glacial aquifer at the base of the valley fill is the Lower Confined Aquifer as identified by Yager et al (2001, 2009, and 2012).

The fractured top of rock (Onondaga Formation), in conjunction with the overlying basal glacial aquifer, form the most critical aquifer zone because of the high transmissivity, the extent of the aquifer across the valley, and the relative freshness of the water at some locations (Dunn Geoscience, 1992; Haley and Aldrich of New York, 1988; Yager et al., 2001, 2009, and 2012; Alpha Geoscience, 2003). The basal glacial Limestone aquifer consists of a mixture of sand, gravel and boulders and contains variable quantities of silt and clay and the basal glacial aquifer together provided most of the water that entered the mine, and as the result of being either a glacial till or glacial outwash deposit. The combined fractured Onondaga

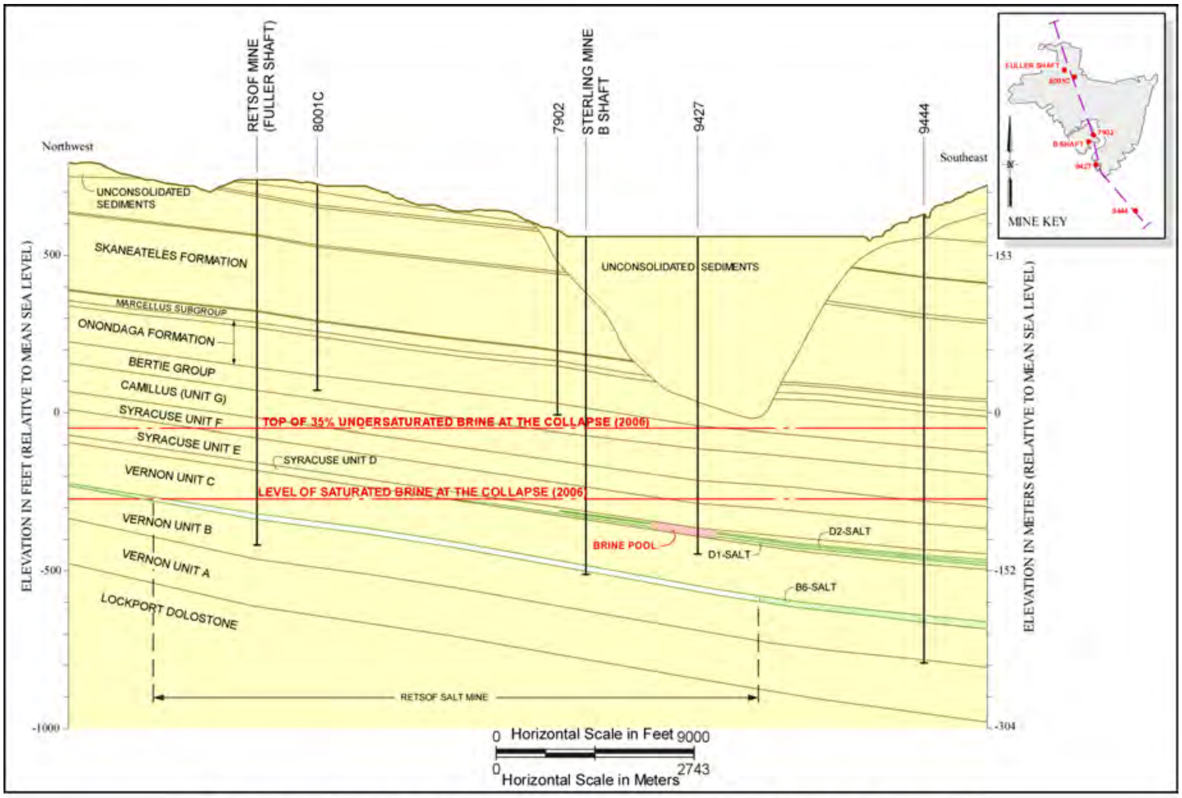

Figure 4. Geologic Cross Section Across the Retsof Mine Area

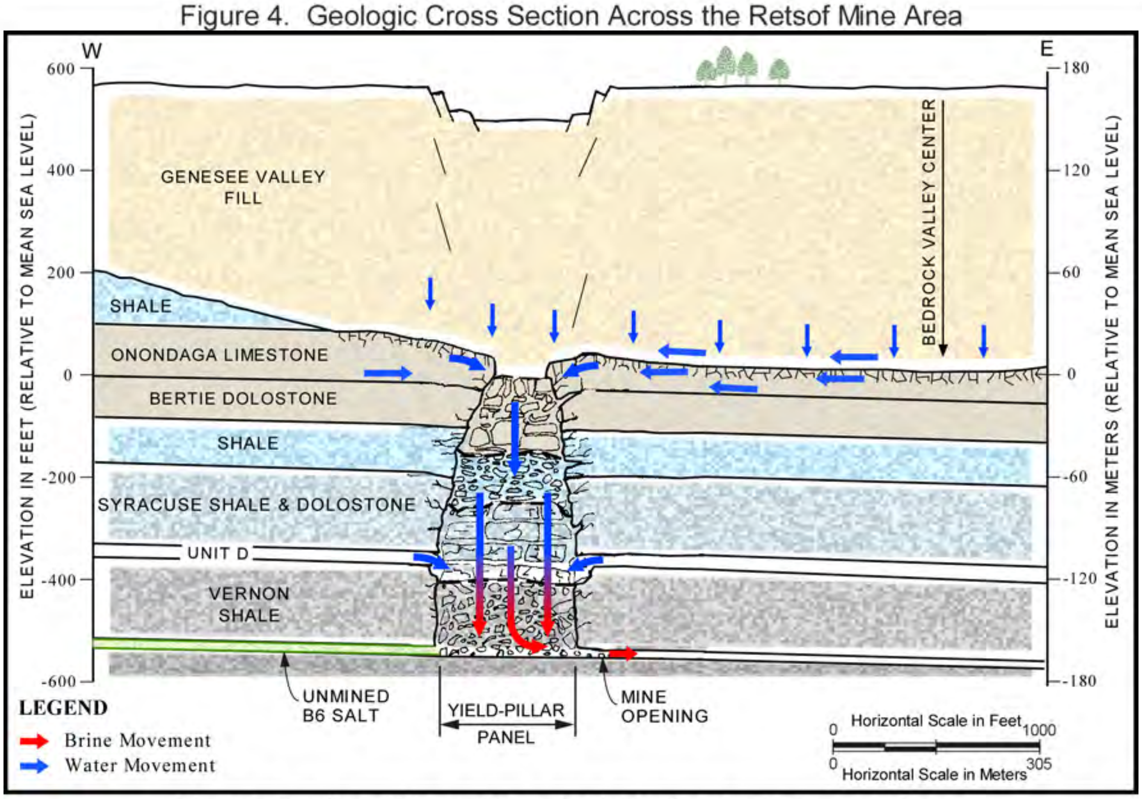

Figure 5. Condition after sinkhole formation at surface.

Limestone and the basal glacial aquifer together provided most of the water that entered the mine, and this aquifer system was considered by the State of New York to have a high potential for future use as a potable water supply.

The Bertie aquifer has limited importance due to poor water quality and limited yield. The Bertie may be connected to the top of rock aquifer through vertical fracturing throughout the valley system. The Unit D brine pool within the Syracuse Formation was of little importance as a source of inflow to the mine due to its limited extent. The Bertie aquifer and the Unit D brine pool are not considered potential water resources for future use.

Rising Brine in the Collapse Zone

It was understood that the gradual compression of the mine was squeezing saturated brine out of the mine, back through the collapse zone and into the overlying aquifers (Figure 6); however, it was not known whether the brine would remain within the deeper, saline bedrock aquifer zones or be pushed up into the basal aquifer system. A monitoring well system was installed in 1996 to track the movement of brine out of the mine and to observe whether the brine would remain in the deeper saline aquifer or be pushed up into the more significant top of bedrock/basal glacial aquifer system. This monitoring well network was initially limited to two basal glacial aquifer wells (9422 and 9568) and two of the top of rock wells (9446 and 9409), which are shown of Figure 7. Salinity, which was monitored in these wells regularly from 1996 through November of 2014, indicated that it had begun to increase in the ground water at the top of rock and in the basal glacial aquifer zone by 2003 as the result of brine rising up through the collapse zone from the mine. Data from the monitoring of zones near the top of the rock at monitoring wells 9409 and 9422 illustrate this steady increase in salinity until a remedial pumping system was started in May 2006 (Figure 8).

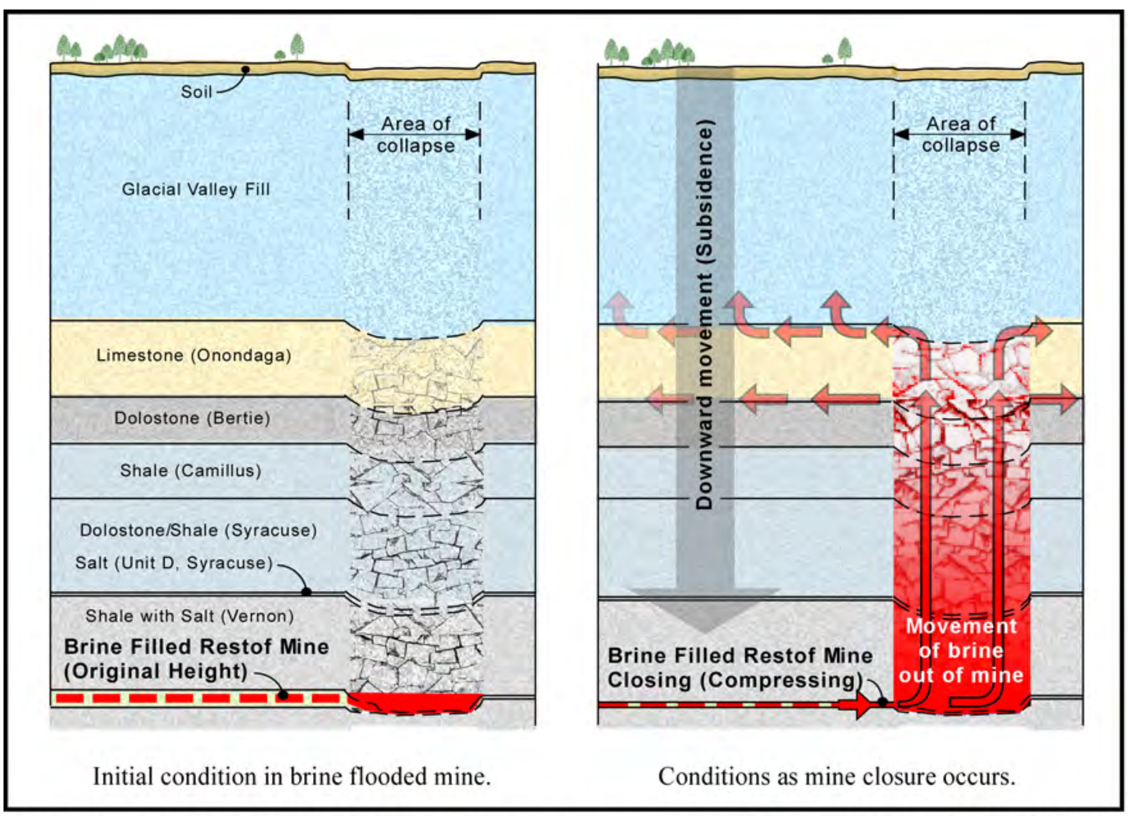

Figure 6. Schematic illustration of brine being squeezed out of the Retsof Mine.

BRINE REMEDIATION PROGRAM

The appearance of mine-impacted saline water at the top of rock triggered a State requirement that the mine owner (Akzo Nobel Salt Incorporated (ANSI)) protect the basal fresh water aquifer system. A brine remedial plan was developed and implemented on behalf of ANSI, in 2004, by: upgrading the monitoring well network around the collapse, increasing the frequency of water level and water quality monitoring, installing and pumping from six (ultimately five) pumping wells, increasing the number of subsidence monuments and constructing and operating a desalinization plant to treat the pumped brine. The program also included geophysical logging of all wells, geochemical modeling, interpretation of the data and reporting of the data and interpretations to the State of New York and other stakeholders.

Monitoring Wells

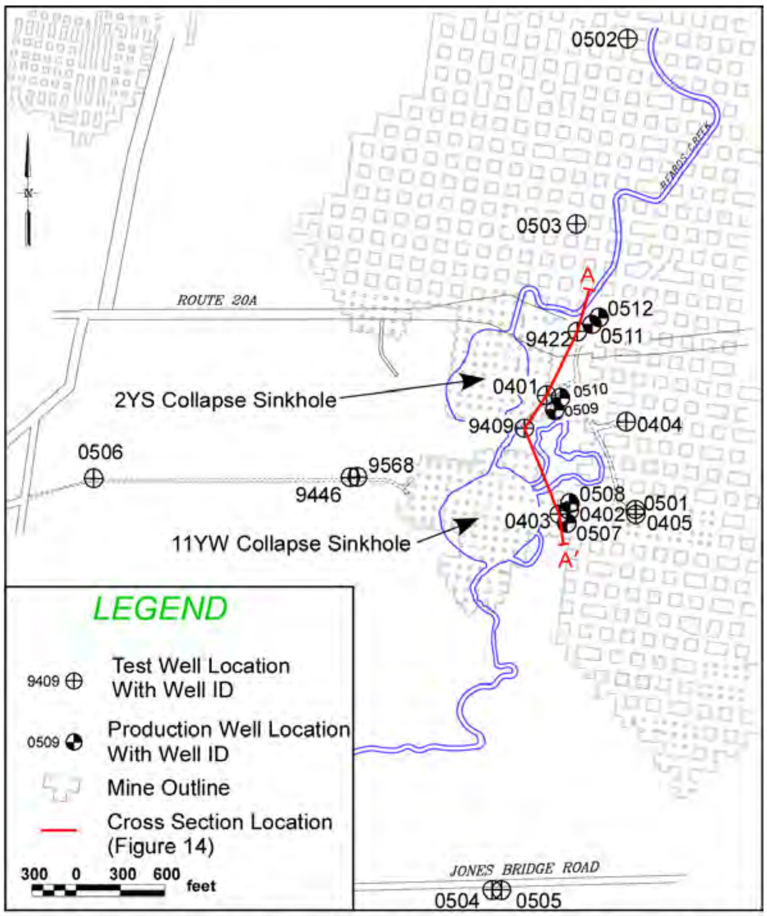

Figure 7. Location Map of Brine Monitoring and Remediation Wells

Eleven new monitoring wells were added to the existing network of four wells in the vicinity of the collapse. This brought the total in the immediate area to 15 wells (Figure 7). A water level and quality monitoring program from the monitoring well network was designed and implemented to maintain real-time knowledge of the vertical and lateral distribution of the brine profile so that pumping-induced changes to that profile were known as close to real time as possible. Detailed knowledge of the vertical and lateral extent of the profile and changes to that profile while pumping also were used to assess the efficacy of pumping and to make adjustments in the pump placements and pumping rates. The effects of remedial pumping were also monitored to prevent dissolution of the salt at mine level or of gypsum and anhydrite minerals in the dolostone and shale layers of Units C and D above mine level (Figures 2 and 4). It was desirable to prevent dissolution of these zones to prevent further catastrophic collapses and sinkhole formation.

Brine Pumping Wells

A total of six wells were installed for pumping on the east side of the collapse area (Figure 7) to provide maximum lateral coverage on the down slope (bedrock valley) side of the collapse. The wells were positioned at these locations to avoid the rock instability within the collapsing chimney while taking advantage of enhanced fracture permeability that was anticipated to occur above the panel entries where inflow-induced dissolution would have been focused. Four of the pumping wells (0507, 0508, 0509, and 0510) were located above the entryways to the collapsed mine panels, and wells 0511 and 0512 were located on the north side of 2YS to provide coverage in accessible areas where more extensive fracturing was also predicted to have occurred as the water was flowing out to the north during the mine flooding phase. The location and spacing of the wells was chosen to allow for an even drawdown of the brine level across the collapse region.

The six wells were grouped into three sets of well pairs. The well pairs were each designed with a shallow and deep well (Figure 9) to cover the 200-ft zone from the middle of the Bertie Group down to

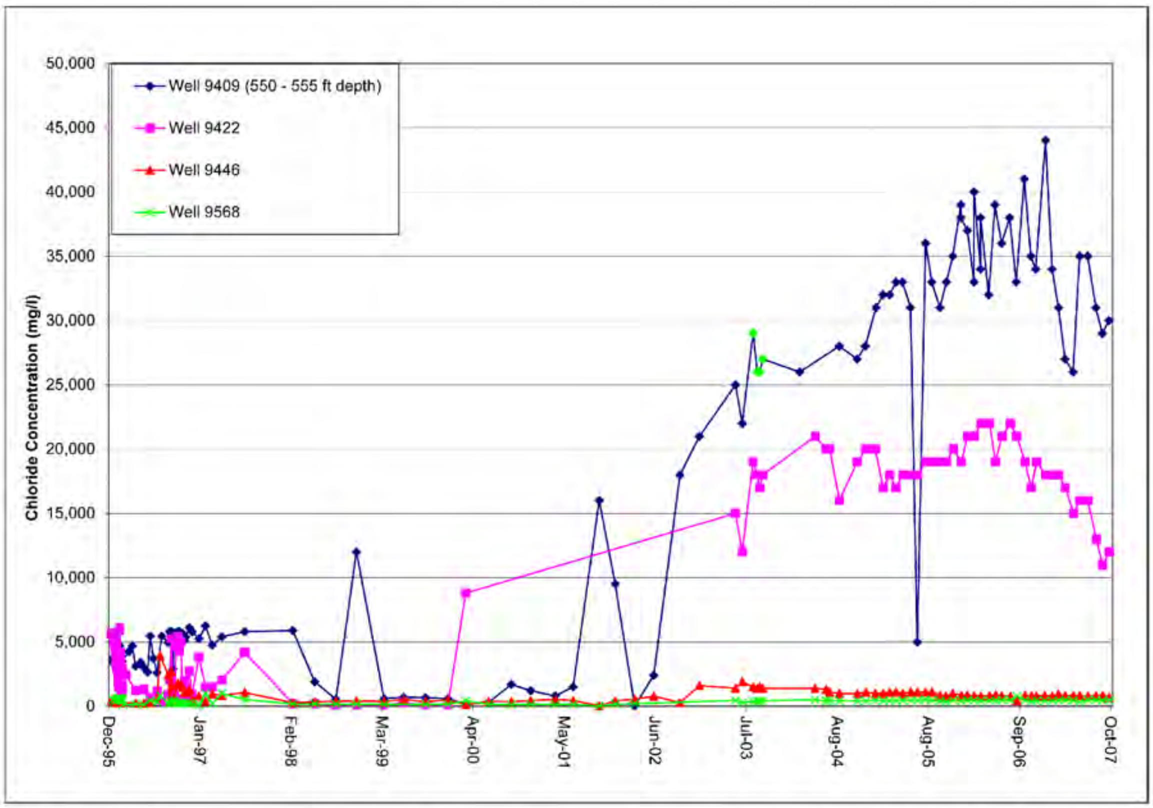

Figure 8. Historical Chloride Concentrations in Wells 9409, 9422, 9446, and 9568 from January 1996 through October 2007

the top of the 100% saturated brine. This interval covers the brine saturation range of approximately 50 to 100 percent. The wells were each designed with a screen length of 100-ft for a total screened interval of 200 ft at each well pair location. This combined interval covered the elevation range from approximately -75 ft bmsl to -275 ft bmsl. The lowest elevation in the deep wells corresponded with the elevation of the mine at its upgradient limit, which is illustrated on Figure 4. This well depth limit was established to avoid drawing the top of the 100 percent saturation line below the elevation of the updip (northern) limit of the mine. This depth limit prevented the potential for further mine-level salt dissolution.

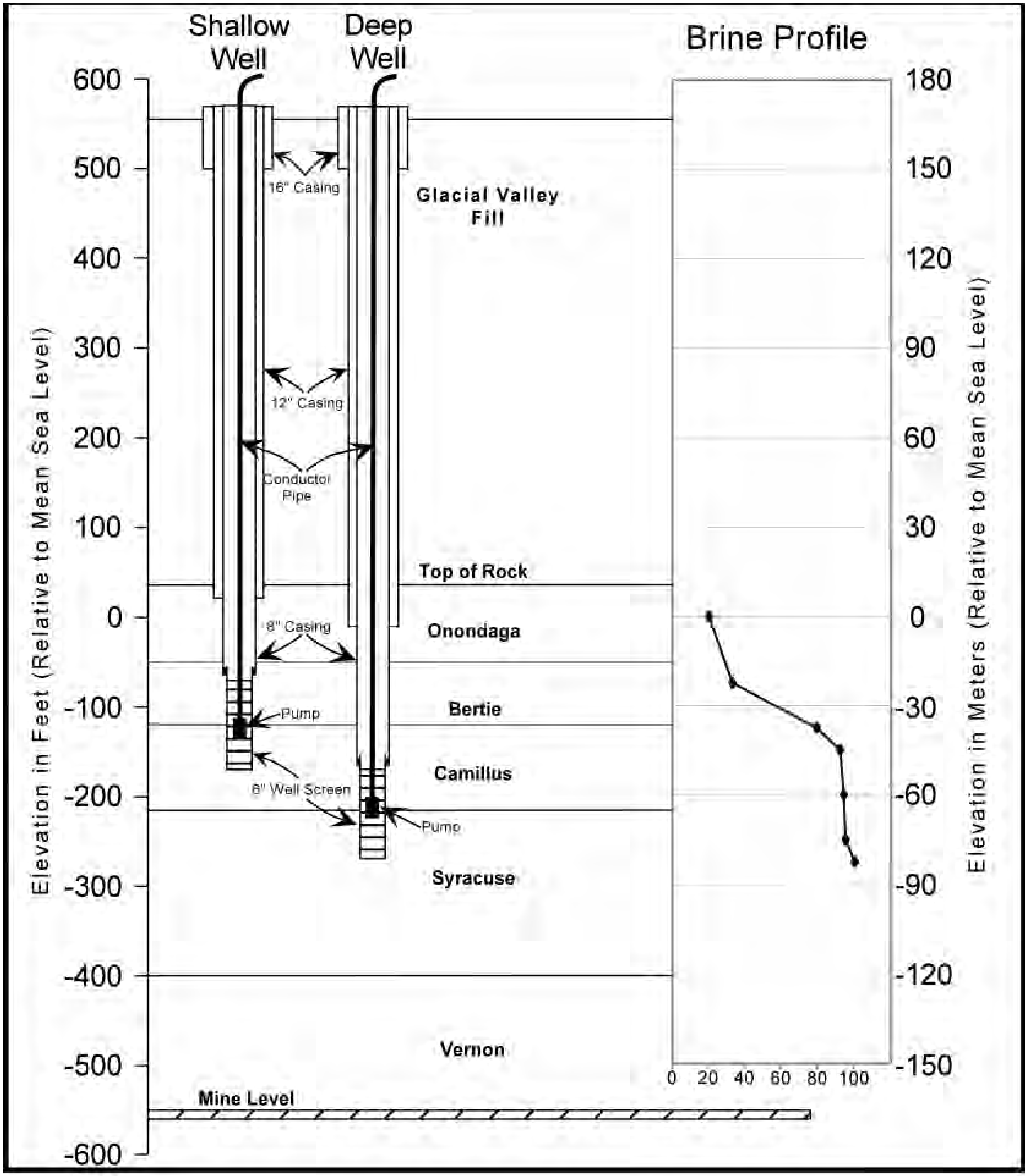

Figure 9. Brine Suppression Well Pairs

The initial pump settings in each respective well were established within the unsaturated portion of the brine profile based on the water quality monitoring and fracture zones identified during drilling and subsequent geophysical logging; however, there was a need for flexibility to respond to actual conditions encountered during pumping. Flexibility was accommodated by designing pump systems that could be adjusted readily to various depths within the 100 ft screen interval in each well. This was accomplished by attaching the pumps to as much as 730 ft of flexible Angus Wellmaster 200 hose (Kidde, 2006) to allow for rapid removal of the pump from the well and to avoid corrosion of steel pipe in contact with the brine. Small sections of stainless steel are used at the top of the assembly to allow for relative easy and quick adjustments to pump intake depths.

The desalination plant had an estimated maximum feed rate from the pumping of 100 gpm. The rate was estimated based on the previously calculated maximum brine squeeze rate of 106 gpm (RE/SPEC, 2003).

The pumping rates of the individual wells ranged from 10 gpm to 25 gpm with a combined rate of 100 gpm. The overall objective was to pump at low enough rates to result in a brine skimming effect to minimize the potential for upwelling of saturated brine by pressure drawdown or the drawdown of fresh water into the profile. The rates in the individual wells were adjusted periodically based on water quality results from each pumping well and the monitoring wells.

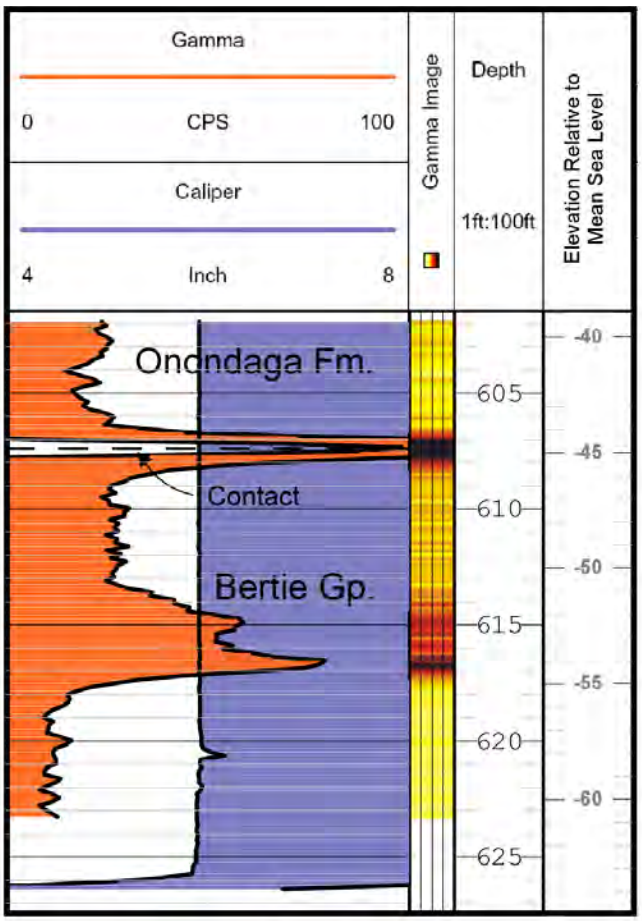

Figure 10. Gamma and Caliper Log of the Onondaga-Bertie Contact.

Geophysical Logging

Geophysical logging has been conducted in fifteen of the monitoring and pumping wells across the site. Gamma-ray and caliper logging tools were applied to confirm the location of significant stratigraphic contacts that were estimated initially from observations during drilling. Figure 10 is an example of the confirmation of the distinctive Onondaga-Bertie contact, which is a significant regional stratigraphic marker and one of the more important water-bearing fracture zones in the Genesee Valley. The location of this and other formation contacts, such as the basal aquifer at the interface between the fractured top of rock and overlying glacial valley fill sediments, were important for the refinement of the ground water monitoring program, the physical visualization of the brine rise, and the development of the geochemical model.

Heat pulse flow logging was conducted in four monitoring wells to detect vertical fluid movement within the wells. The intent of this logging was to measure fluid movement in order to quantify hydraulic flow potentials between fracture sets in the bedrock; however, the initial results showed no measurable flow. Apparently, the vertical flow was below the detection limit of the equipment despite the fact that water level monitoring indicated vertical pressure gradients between fracture sets within each hole.

Caliper and acoustic televiewer logging were used to locate specific fractures and correlate fracture sets between wells. Optical televiewer logging was attempted in the wells but was unsuccessful due to discoloration caused by hydrogen sulfide. The acoustic televiewer logs in Figures 11, 12 and 13 graphically represent an example of a fracture set that is correlatable throughout the collapse area. The televiewer log of well 0510 displays an extensive fracture set from a depth of 664 ft below grade (bg) to 674 ft bg (Figure 11). The log from well 0508 (Figure 12), which was located approximately 700 ft down dip from well 0510, displays a similar fracture set from 672 ft bg to 677 ft bg. The third shallow pumping well 0512 (Figure 13), which was located approximately 600 ft updip of 0510, displays fractures within the 670 ft bg to 680 ft bg depth range that are less numerous and not as well developed as those noted in wells 0508 and 0510. These results suggest the presence of a fracture zone that could be laterally extensive and transmissive in the rock interval above the collapse entries but diminishes further away from the collapse area (Figure 14).

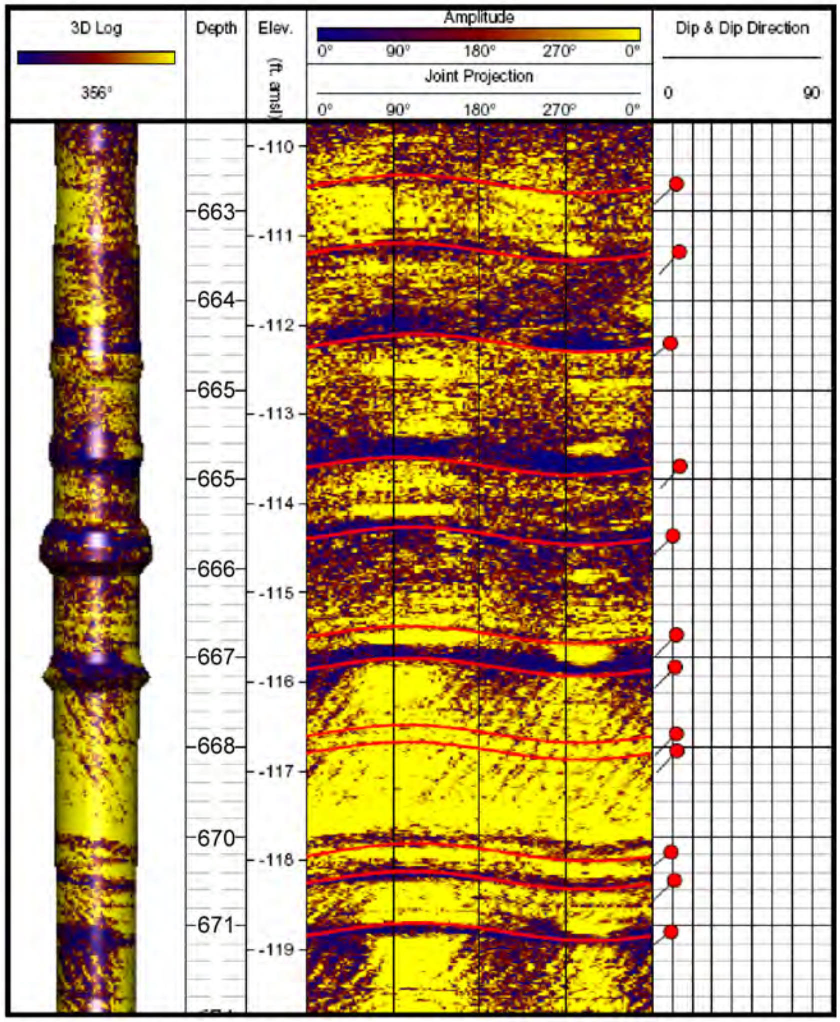

Figure 11. Acoustic Televiewer Log of Production Well 0510.

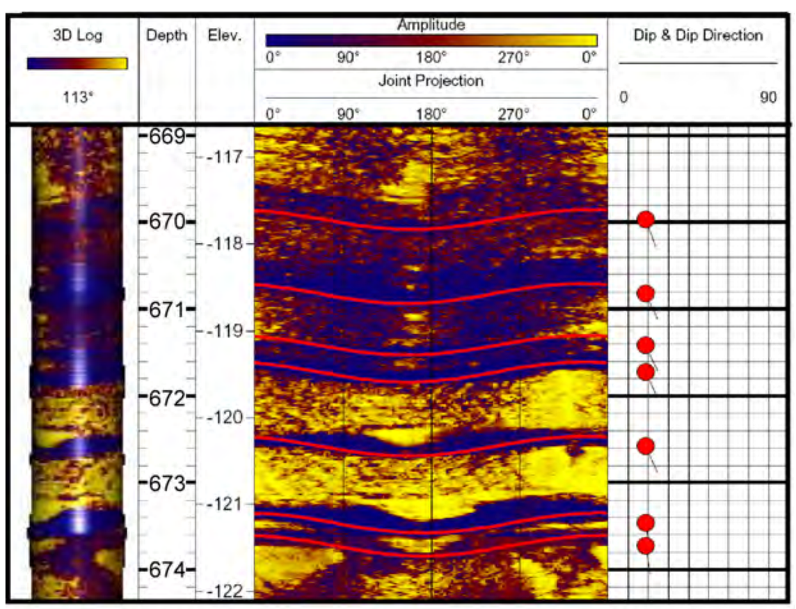

Figure 12. Acoustic Televiewer Log of Production Well 0508.

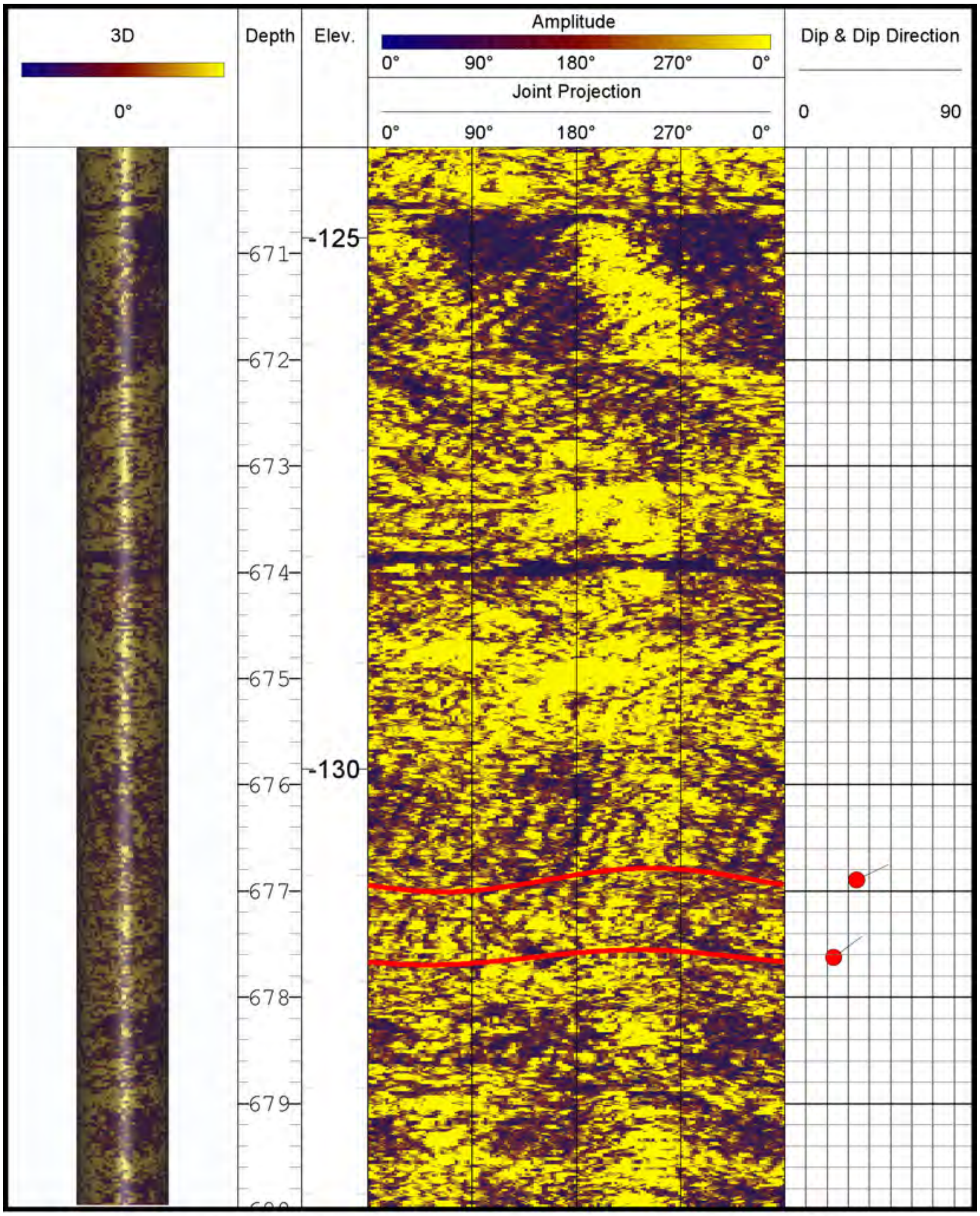

Figure 13. Acoustic Televiewer Log of Production Well 0512.

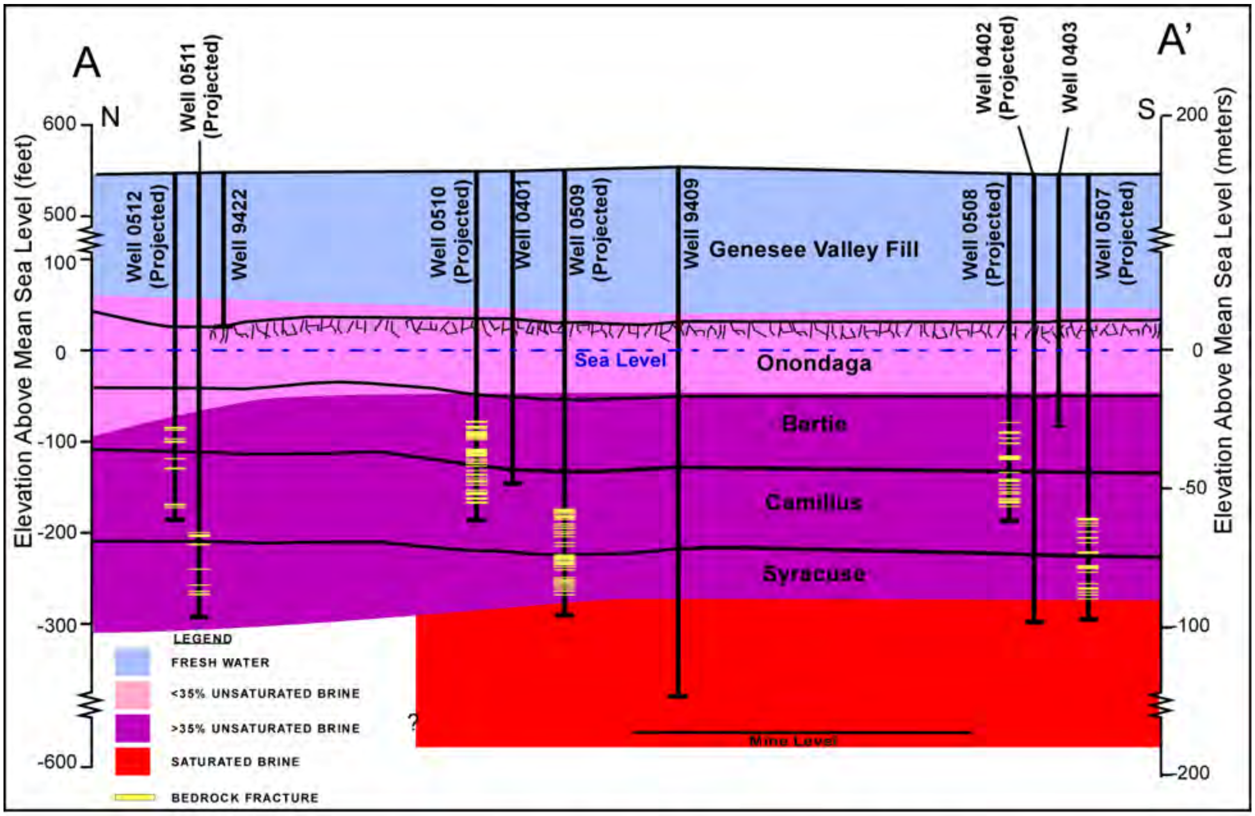

Figure 14. North-South directed cross section through monitoring and remediation wells showing the location of significant fracture sets.

Laterally extensive and potentially transmissive fracture sets were found elsewhere within the 200 ft interval intersected by each well pair. The shallow wells, (0508, 0510, and 0512) display an extensive fracture set between 635 ft bg and 655 ft bg. Two of the deeper wells (0507 and 0509) were found to have extensive fracturing across the entire 100 ft zone. Well 0511 displayed less extensive fracturing and fewer sets than the other deeper wells, likely because there was less dissolution and subsidence in this area than originally predicted. The placement of the pumps in each well was based upon the potential transmissivity of the fracture sets and the concept of lowering the brine concentration via the skimming effect. The existence of multiple fracture sets that are laterally extensive allowed for the installation of the pumps at varying depths/elevations across the region.

Water Quality and Hydraulic Flow Monitoring

Field salinity was tested at specific horizons throughout the collapse area to chronicle the rate and nature of changes in the brine profile. This testing was the primary focus of the water quality monitoring program. The particular horizons of interest included the top of bedrock, the 35% saturated brine level, and the top of the 100% saturated brine level.

Hydraulic flow monitoring within the collapse vicinity was conducted to quantify brine and saline water movement. The monitoring consisted of collecting hydraulic head (water level) measurements associated with the Onondaga-Bertie contact and mean sea level elevation across the region. The water level data collected from the wells had to be adjusted to equivalent pressure head of fresh water by multiplying the column height above the measuring points by the density of the fluid.

Geochemical Modeling

Geochemical modeling was utilized to simulate the dissolution and precipitation of minerals as the salinity. This is being accomplished by using PHREEQC (Parkhurst and Appelo, 1999) to calculate saturation indices that would result when subsurface layers containing anhydrite and gypsum are exposed to water with a range of chemical characteristics. Saturation indices represent the potential for minerals to dissolve or precipitate in a solution (Freeze and Cherry, 1979). Saturation indices of halite and anhydrite were calculated for the historical data set and trends were established for the pre-pumping environment. These indices were monitored during the pumping of brine to watch for sudden or drastic changes from the baseline trends in order to determine if dissolution was occurring at specific zones.

Subsidence Monitoring

Monitoring of the pre-existing surface subsidence monument network in the collapse region was used to detect short-term increases in subsidence related to pumping activities and to track the overall subsidence rate above the mine. This monitoring was conducted during the design and construction of brine mitigation plan to provide pre-pumping background information. Each set of data was evaluated to detect localized changes in elevation during pumping that could have been indicative of collapse related to pumping-induced dissolution. The subsidence data was also used as a proxy for mine closure which is directly related to the brine squeeze rate. This squeeze rate was coupled with the water quality monitoring to assess the percentage of pumped brine that was coming from the mine and the amount that may have been pre-existing in the saline aquifers below the top of the rock.

RESULTS OF THE BRINE REMEDIATION PROGRAM

The installation of additional monitoring wells was completed in 2005. Some of these wells were completed with multi-level tubing for monitoring various depths within the brine profile. A few of the wells were also completed with multi-level packers, but those proved to be ineffective due to vertical fracture connection around the packers, and the packers proved to be unnecessary due to high transmissivities in the wells and the density stratification in the brine profile.

The pumping wells were completed in 2006, and pumps were installed in five of these wells. No pump was installed in Well 0512 due to low yield as the result of limited fractures. Pumping was initiated in late May 2006 after a desalinization plant was constructed at the site. The wells were pumped intermittently until February of 2007 due to the need to modify the plant to accommodate the challenges of processing a multi-chloride brine that contained Mg/Ca/NaCl and several other constituents such as sulfate. The system was operated successfully with relatively continuous pumping from February 2007 through mid-December 2013 when the State of New York allowed ANSI to shut down the remediation system during negotiations to determine the future of the remedial program. The brine profile monitoring continued through November 2014 when it was determined that no further remediation was required.

Pre-Pumping Brine Profile and Hydraulic Pressures

The brine profile through the collapse zone, as it appeared in November 2005 (six months prior to initial pumping), is illustrated on a west-east cross section through the collapse chimney (Figure 15). It was apparent to Alpha Geoscience (2003) and The U.S. Geological Survey (Yager et al, 2009) that a significant percentage of the saline water (bedrock zone with less than 35% saturation) was a brine that pre-dates the collapse. This pre-existing brine was being displaced and partially mixed with the upwelling, minederived brine. The domed surface of the more saturated, upwelling brine illustrated by Figure 15 is based on a percent salinity map (Figure 16) that represents conditions at the regionally extensive aquifer at the Bertie/Onondaga contact as it existed in November of 2005. The highest concentration is

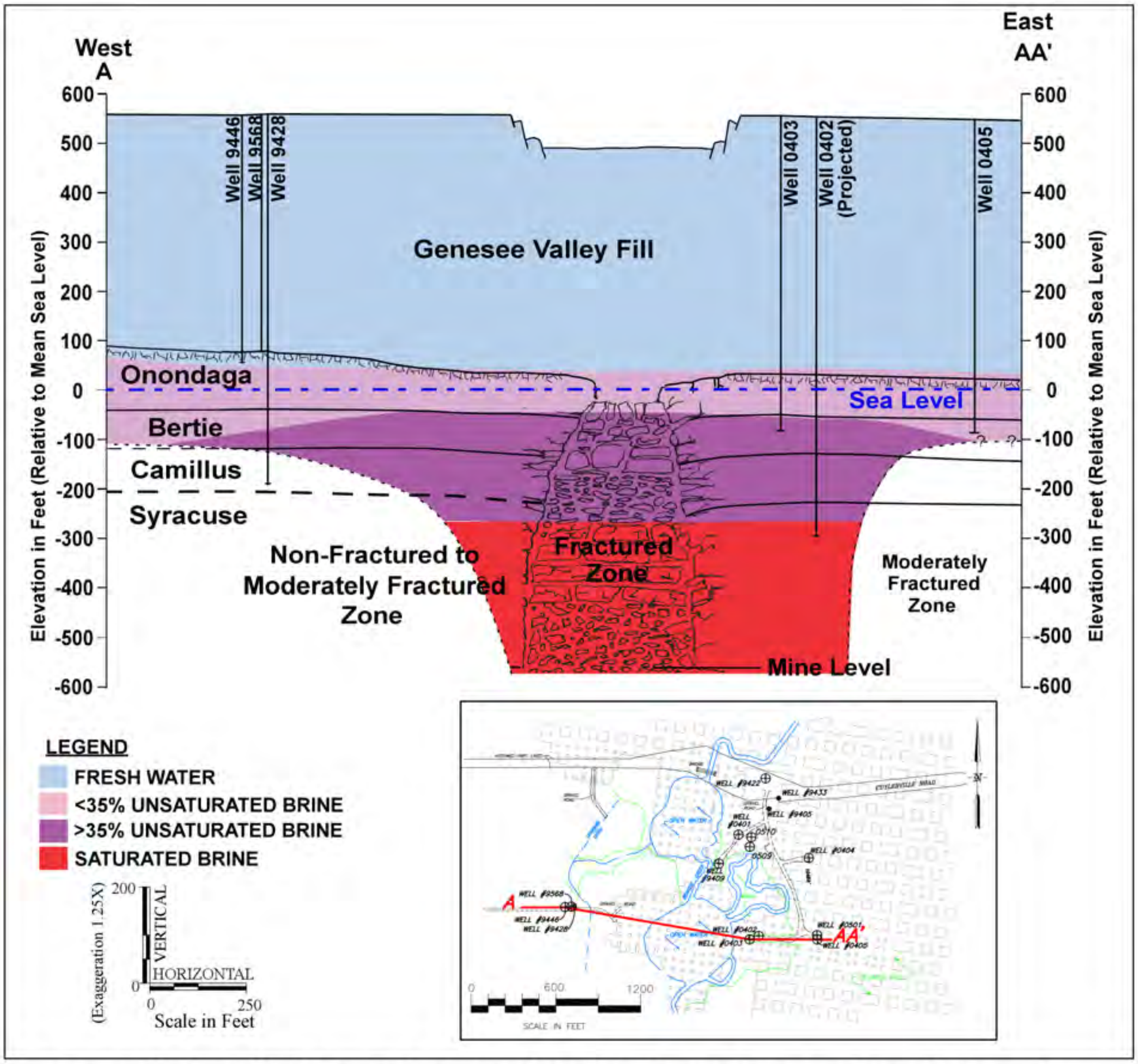

Figure 15. East-West directed cross section through monitoring and remediation wells showing upwelling brine

centered at the two adjacent collapse chimneys represented by the open water of the surface sinkholes.

The brine upwelling indicated by the saturation map is consistent with the distribution of pressures at the Onondaga/Bertie contact (Figure 17). This map shows a distinctive pattern of pressure mounding and outward radial flow centered on the collapse chimneys.

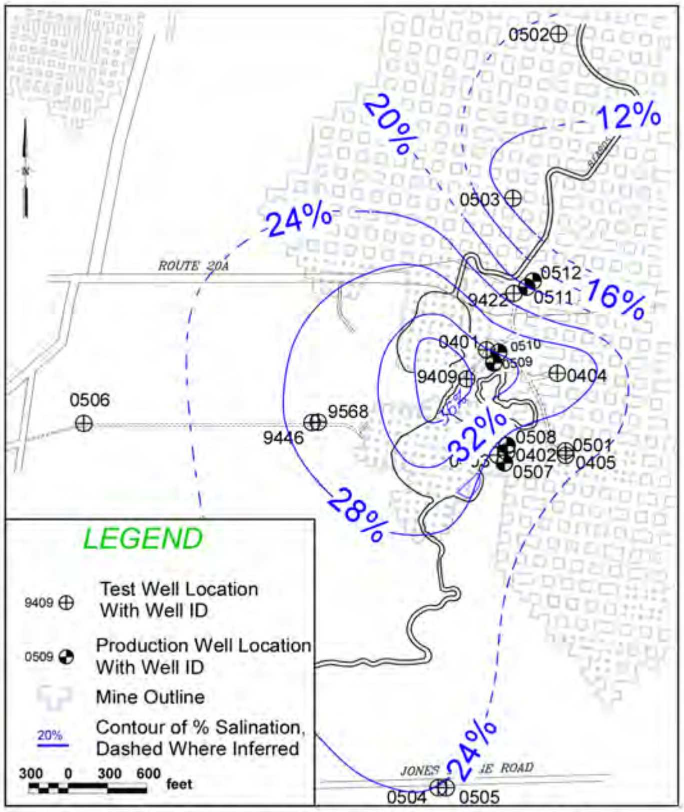

Figure 16. Percent Salinity Contour Map at Mean Sea Level, November 2005

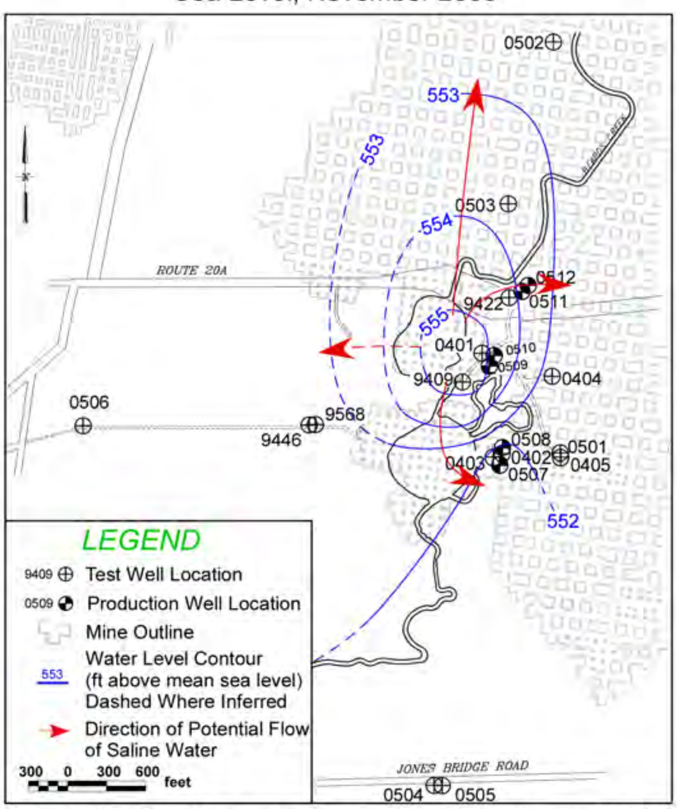

Figure 17. Contour map of water level elevations at the Mean Sea Level, November 2005

Brine Profiles and Hydraulic Pressures during Brine Pumping

The brine saturations at the top of rock essentially stopped increasing at the start of intermittent pumping in May of 2006 and were clearly decreasing after more continuous pumping began in February of 2007 (Figure 8). Pumping-induced drawdown effects at the Bertie/Onondaga contact are evident on the hydraulic head pressure contours for July 2013 (Figure 18). A contour map for chloride concentration at mean sea level in July 2013 shows the reduction in salinity in the collapse zone (Figure 19).

The pumping was spread out over the east side of the collapse zone with the intent of not creating significant drawdown or upwelling effects. This was achieved and allowed the maintenance of stable pressures through an increase in water levels as the denser brine was replaced by less saline water. This is illustrated by the increase in measured fluid level at the Onondaga/Bertie contact that was correlated with a decrease in salinity (field measured density) as the pumped brine was replaced by less saline fluid (Figure 20). This increase in water levels related to a decrease in salinity (density) required an adjustment (normalization) of all field measured salinity (density) to a fresh water equivalent hydraulic head for piezometric mapping purposes.

Post-Pumping Conditions

Pumping was discontinued in December of 2013, and there was a more immediate response exhibited by an increase in salinity and a corresponding decline in directly measured fluid levels in response to the increase in fluid density (Figure 21). For example, the saturation at the Onondaga-Bertie Contact increased by approximately 10%, and the directly measured fluid level declined by approximately 10 feet in Well 0403.

All monitoring was discontinued after November 2014. The wells were plugged and abandoned in 2015 and 2016, and the brine treatment plant was dismantled in 2015. This closure activity was conducted through a settlement agreement between ANSI and the stakeholders.

Summary of Geochemical Modeling and Subsidence Monitoring

The geochemical modeling was focused towards the pumping effects on dissolution in the anhydrite-bearing formations below the Onondaga-Bertie Contact. The ideal condition was to have a saturation index close to zero. The data input into the PHREEQC model resulted in a high potential for anhydrite dissolution above the anhydrite-bearing Camillus Shale, as illustrated in Well 9409 (Figure 22), but little or no apparent potential at the more critical anhydrite-bearing zones below that level. No dissolution conditions occurred during the pumping test for either the anhydrite or the more soluble halite intervals. These results are consistent with the subsidence data, which did not show any evidence of differential (sinkhole-type) settlement occurring throughout the area.

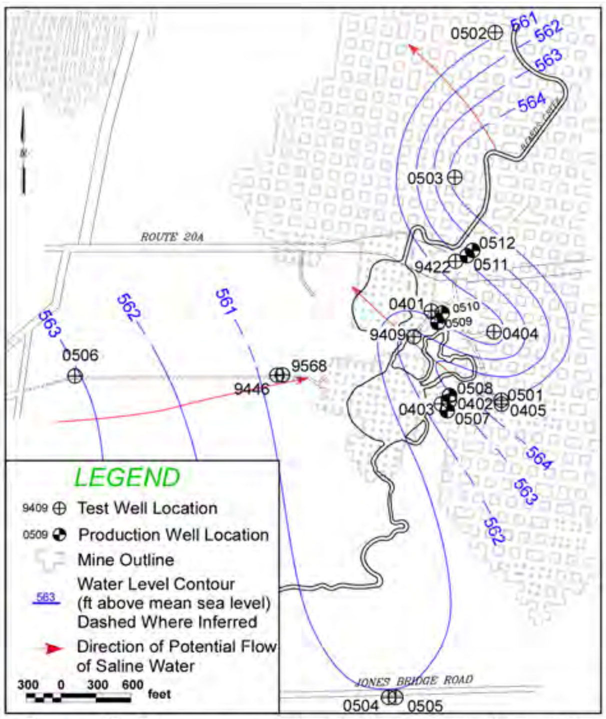

Figure 18. Contour map of water level elevations at the Onondaga-Bertie Contact, July 2013

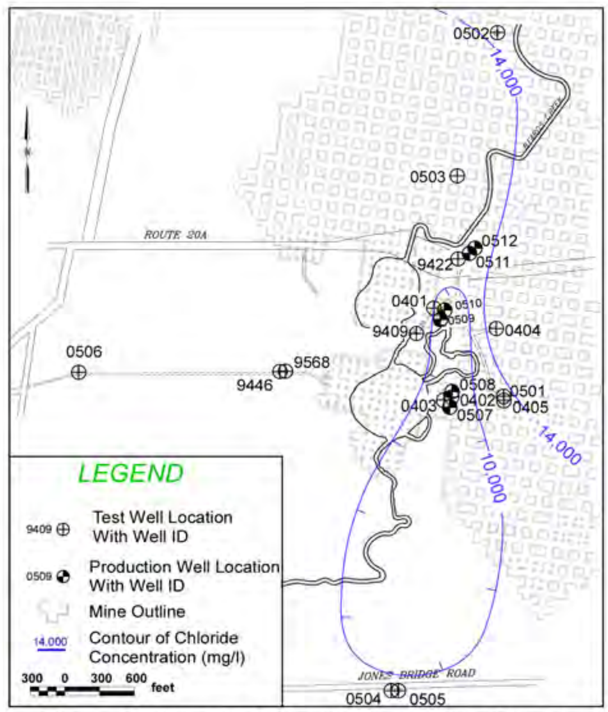

Figure 19. Chloride Concentration Contour Map at Mean Sea Level, July 2013

The subsidence monitoring data showed that subsidence above approximately 47 percent of the mine was effectively zero. The remaining 53 percent of the footprint had a subsidence rate that was equivalent to a brine squeeze rate of 15.7 gallons per minute (gpm) with a range of +/- 4 gpm. This rate was well below the maximum estimated squeeze rate of 106 gpm and had apparently declined significantly due to the buoyancy effects of hydrostatic pressure. It is estimated that it would take approximately 2,240 years for the 11.2-square mile mine to push out all of the brine at the current closure rate; however, the non-measurable rate of subsidence over approximately half of the mine footprint suggests that further declines in the closure rate will occur, and ultimately, the mine closure will approach zero.

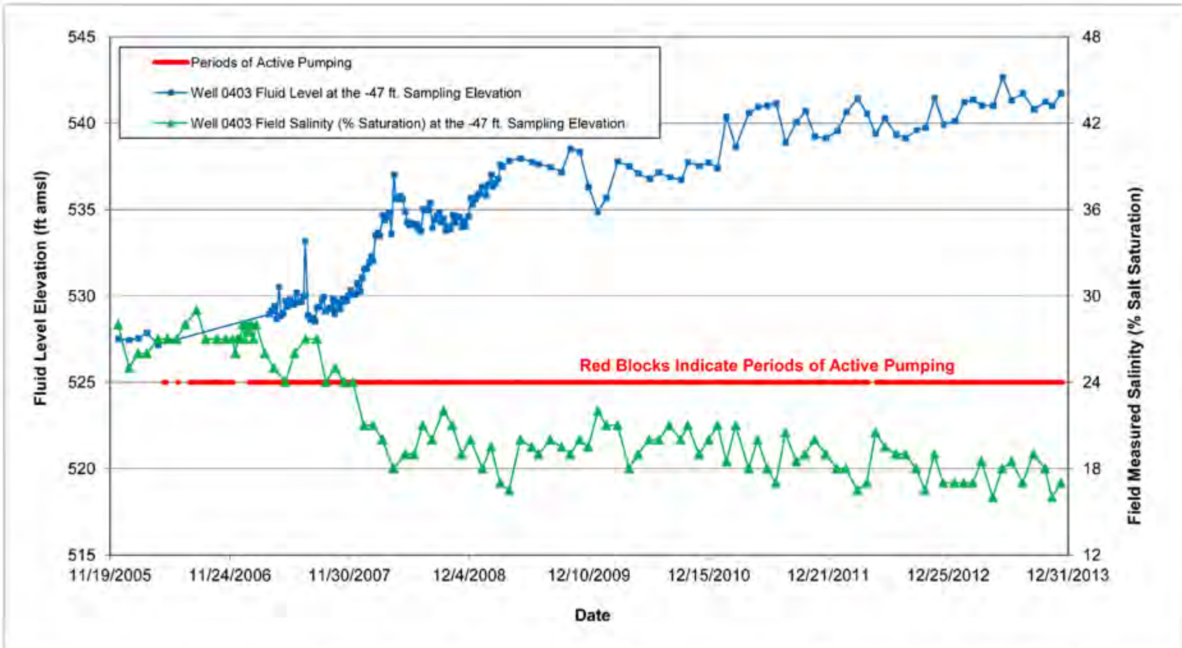

Figure 20. Unadjusted Fluid Level Elevation vs. Field Measured Salinity, Well 0403 at the Onondaga - Bertie Contact (-47 ft. Sampling) Elevation

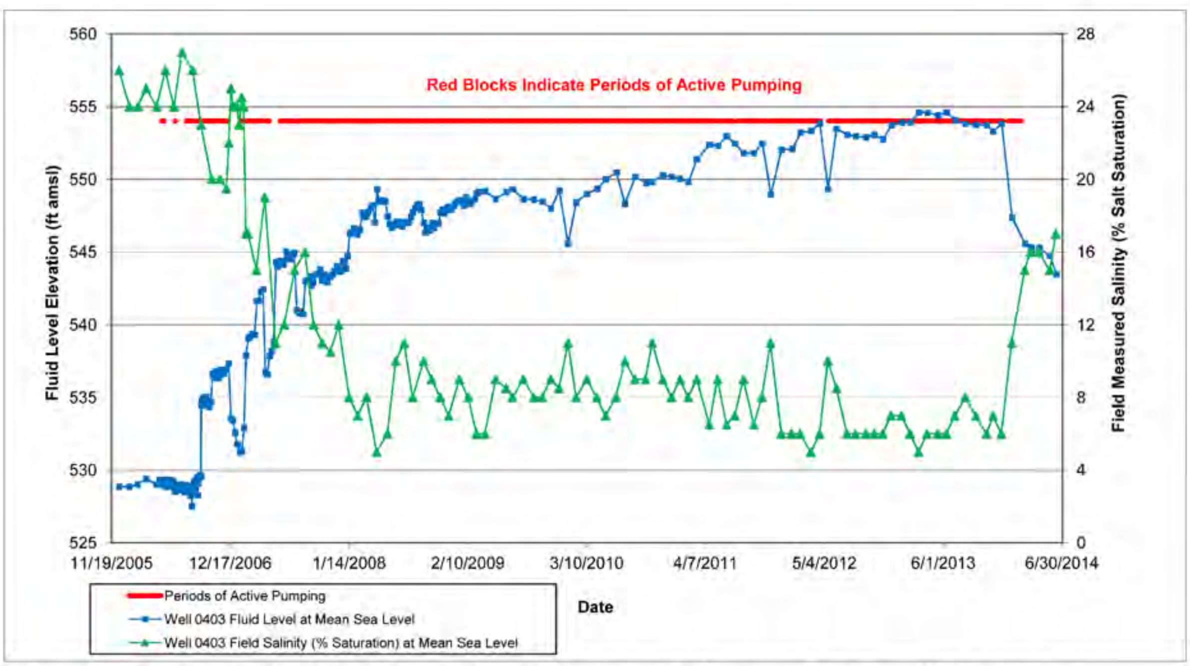

Figure 21. Unadjusted Fluid Level Elevation vs. Field Measured Salinity, Well 0403 at Mean Sea Level Elevation

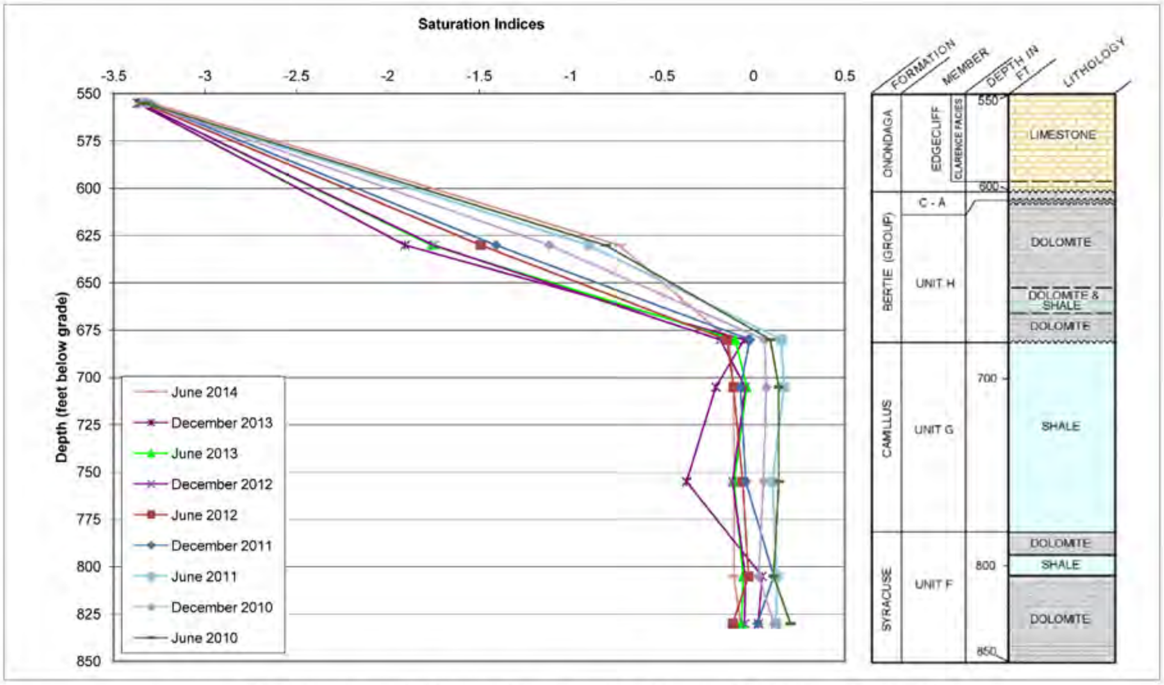

Figure 22. Anhydrite Saturation Index Versus Depth at Well 9409

CONCLUSION

The ANSI brine remediation project at the collapsed Retsof Salt Mine yielded detailed data about the stratigraphy and hydrogeology of the bedrock and glacial deposits in the mine collapse area. This detailed data, which included vertical water quality profiles throughout the collapse area, showed that the brine was being squeezed out of the Retsof Mine and up through the collapse zone chimneys toward a fresh water aquifer at the top of the rock and base of the overlying glacial sediments. The data provided the basis for developing a brine remediation system consisting of pumping from the unsaturated zones of the bedrock adjacent to the collapse chimneys. The objective of the remedial pumping was to prevent the brine from entering the fresh water aquifer at the top of the rock. The results demonstrated that this remedial objective was achieved while pumping. The results also demonstrated that pumping was occurring at a higher rate than the rate that the brine was being expelled from the mine and that some of the brine being extracted by pumping was pre-existing saline water that was located within the fractured bedrock aquifer system and locally within the glacial aquifer base above the mine.

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