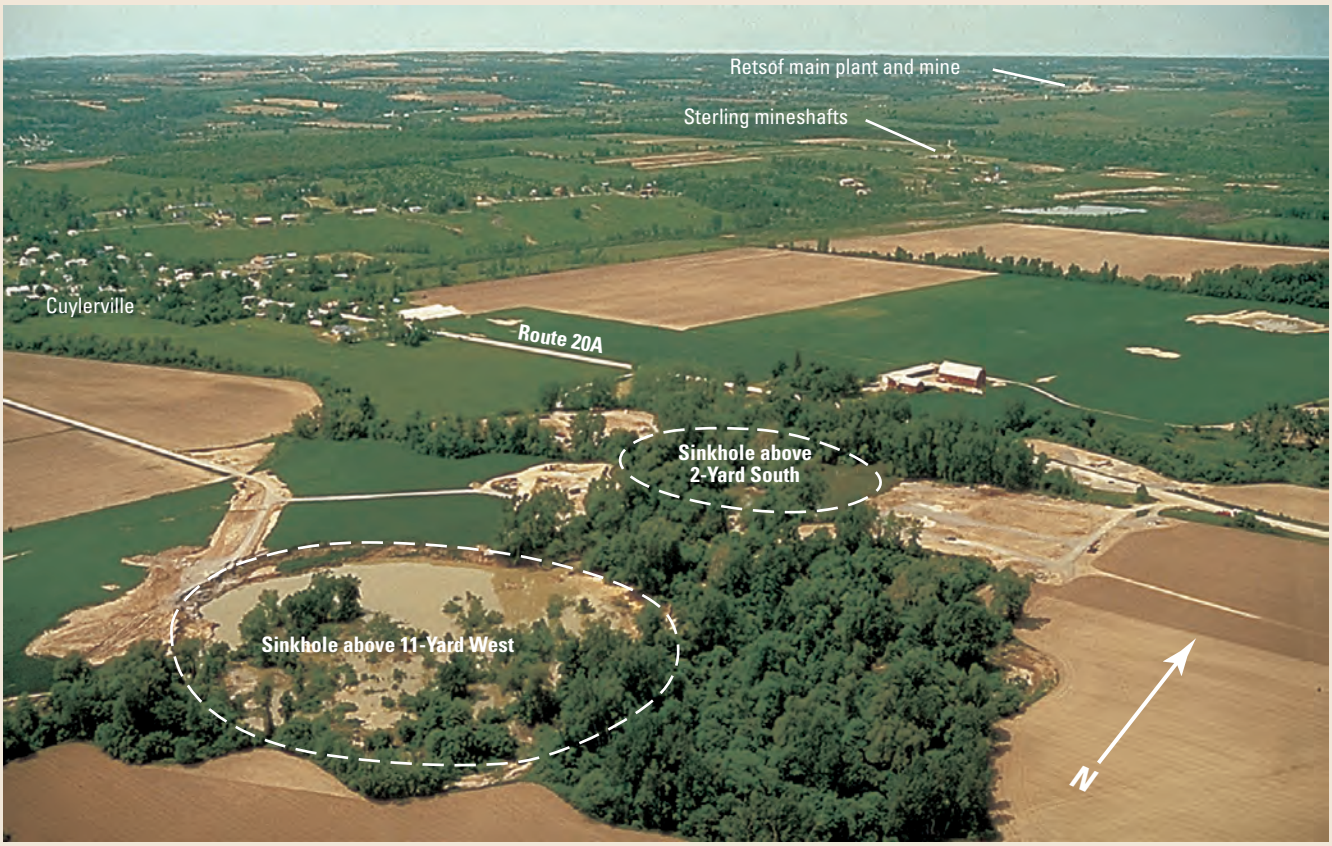
Prepared in cooperation with the New York State Office of the Attorney General

# Simulated Flow of Groundwater and Brine from a Flooded Salt Mine in Livingston County, New York, and Effects of Remedial Pumping on an Overlying Aquifer




Courtesy of Ron Pretzer/LUXE, May 1994

This northwest aerial view shows sinkholes above room 11-Yard West (left foreground) and room 2-Yard South (right center, partially obscured by trees) of the Retsof salt mine. The Retsof main plant is located about 4 miles northwest of the sinkholes.

Simulations of the movement of brine from a flooded salt mine near Geneseo, New York into an overlying aquifer indicate the following effects, if remedial pumping were discontinued:

- Saline water from bedrock would flow upward toward an overlying aquifer through rubble chimneys in bedrock that hydraulically connect the flooded salt mine to the aquifer. Halite brine from the mine would eventually reach the aquifer along the same path.
- Dense saline water that reaches the aquifer through the rubble chimneys would migrate southward along the sloping bedrock surface to its lowest point south of the mine.
- A pool of saline water would form in this depression and extend northward and southward as the flow continues; however, the high relative density of the saline water would probably prevent it from rising into other overlying aquifers.
- The fate of mine water (brine) that enters bedrock fracture zones that intersect the rubble chimneys is uncertain. Some might emerge updip to the north, where a limestone subcrop area intersects the bedrock surface. The traveltime, however, cannot be calculated from available information.

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## Introduction

Two ceiling collapses in the Retsof salt mine near Geneseo in upstate New York (fig. 1) in spring 1994 resulted in the upward propagation of two columns of rubble through 600 feet of overlying shale and carbonate bedrock (fig. 2). This upward propagation formed a hydraulic connection between the lower confined aquifer (LCA) and the mine and allowed water from the aquifer and bedrock fracture zones that intersected the rubble columns to flow into the mine at a rate of 18,000 gallons per minute (gal/min) (fig. 3, steps 1–2). All salt mining ceased in September 1995, and the mine was completely flooded by January 1996 (figs. 1B; fig. 3, step 3).

The flow of water from the lower confined aquifer into the mine caused widespread drawdowns, and water levels in the aquifer declined by as much as 400 feet near the collapse area and by more than 50 feet at wells 7 miles to the north and south. Within 3 to 4 weeks of the collapses, water levels in about a dozen domestic and industrial wells had declined severely, and some wells went dry. Water levels in at least 58 wells in the lower and middle confined aquifers were affected by mine flooding. Groundwater in the upper unconfined aquifer and surface water in streams were unaffected by water-level drawdown, but channels of the Genesee River and Beards Creek (fig. 1) were altered by land subsidence related to the mine collapse.

Photograph by Richard Young, Geological Sciences, State University of New York Geneseo, May 1994

In April and May 1994, sinkholes formed when rubble chimneys extended upward from the Retsof salt mine to land surface (about 1,100 feet). The formation of the sinkholes lowered the streambed of Beards Creek (shown above), a tributary of the nearby Genesee River, and water from the creek flooded the sinkholes. Eventually, both sinkholes measured 200 feet in diameter (cover photo).

Photograph by William Kelly, New York State Geological Survey, June 1995

Picture shows rising water in the Retsof salt mine in June 1995, following the collapse of two ceiling areas in the mine near Cuylerville, New York, on March 12, 1994. A pump out was attempted and abandoned. Mining ceased in September 1995, and the mine was flooded by January 1996.

Water levels recovered from 1996 through 2006 (fig. 3, step 4), but the mine is now filled with about 16 billion gallons of saturated halite brine. The weight of the overlying rock and sediment is expected to cause the salt beds to deform and fill the mine cavity during the next several hundred years; this in turn could displace as much as 80 percent of the brine and cause it to move upward through the rubble chimneys, rendering the LCA unusable as a source of water supply. Saline water was detected in the LCA in 2002 but was found to be derived primarily from fractures in the limestone and shale units between the mine and the LCA, rather than from the mine.

In September 2006, the mine company began a brine-mitigation project that entailed pumping five wells finished in limestone and shale units within the collapse areas to alter the flow gradient and thereby prevent further movement of brine and saline water into the LCA (fig. 3, step 5). The pumped brine was routed to an onsite desalination plant. At the same time, the U.S. Geological Survey (USGS) began a study in cooperation with the New York State Office of the Attorney General to construct numerical models to analyze the groundwater chemistry and delineate the directions of flow. Specific objectives of the study were to:

- Assess the sources of salinity within the collapse area and identify the factors that control the movement and mixing of freshwater, saline waters from fracture zones, and brine;
- Evaluate the likelihood that the pumping will induce anhydrite dissolution and lead to continued land subsidence;
- Construct variable-density groundwater flow models to predict the effect of remedial pumping on salinity within the LCA;
- Evaluate the effectiveness of remedial pumping in preventing the movement of saline water into the LCA; and
- Predict the extent of brine migration 8 years after a hypothetical shutdown of all pumping in 2008.

This report (1) summarizes the hydrogeologic setting and effects of mine flooding, (2) describes the geochemical and variable-density model simulations and their principal results, (3) discusses the implications of (a) continued pumping and desalination to protect the LCA and (b) a full shutdown of pumping after 2008, and (4) suggests further research that could lead to refinement of model predictions. Additional information may be found in Yager and others (2001 and 2009). These reports can be accessed at http://pubs.usgs.gov/pp/pp1611/ and http://pubs.usgs.gov/pp/pp1767/, respectively. A summary of simulation results can be accessed at http://ny.water.usgs.gov/projects/Coram/seawat/seawat.html.

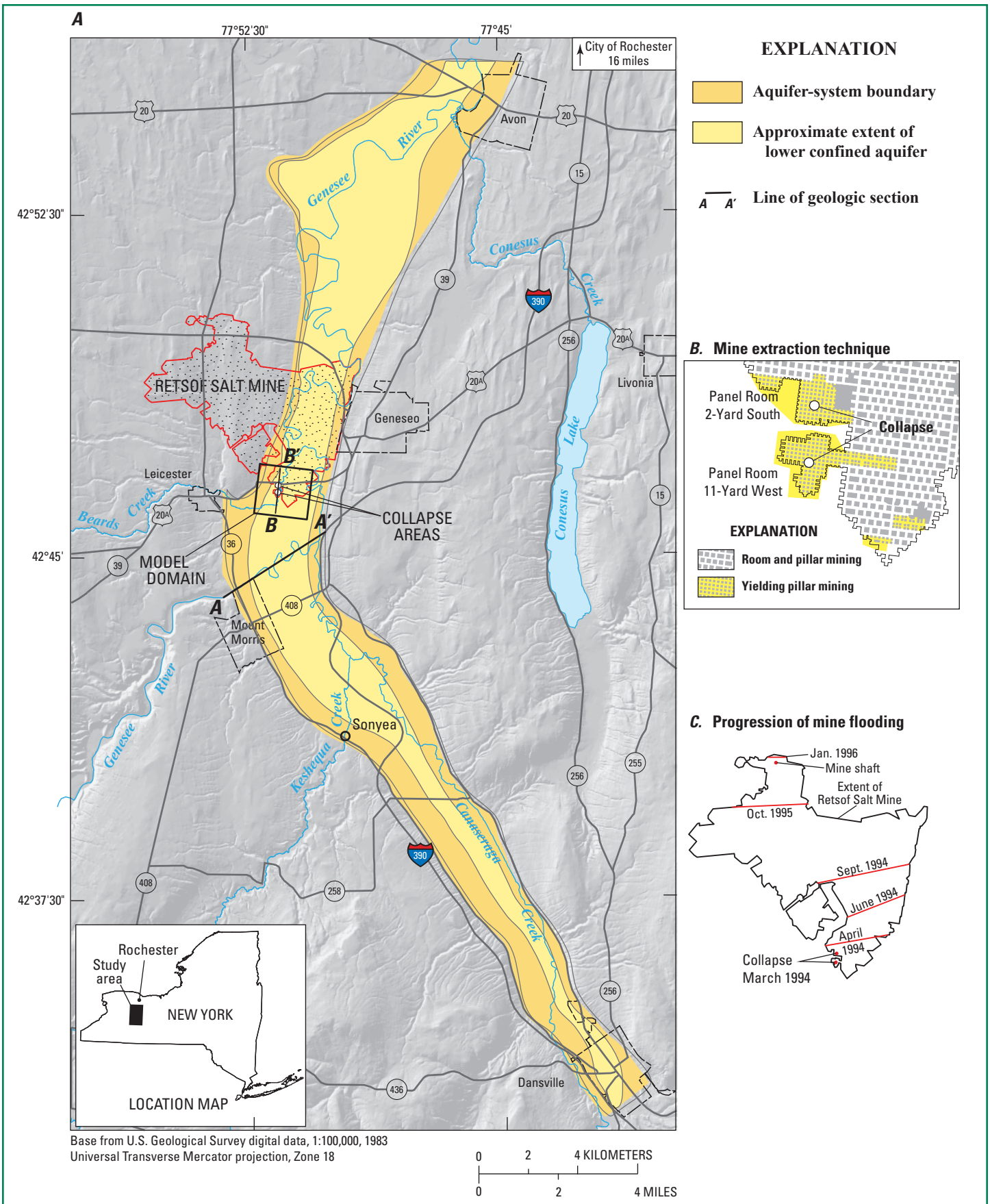



**Figure 1.** *A,* Map showing locations of the Retsof salt mine and the two ceiling-collapse areas, and the extents of aquifers near Geneseo in Livingston County, New York. Adapted from Yager and others (2009, fig. 1.) *B,* Plan view showing small pillars in panel rooms 2-Yard South (2YS) and 11-Yard West (11YW) where ceiling collapse occurred. *C,* Map showing extent of Retsof salt mine and progression to complete flooding of the 5-mile by 5-mile mine in January 1996.

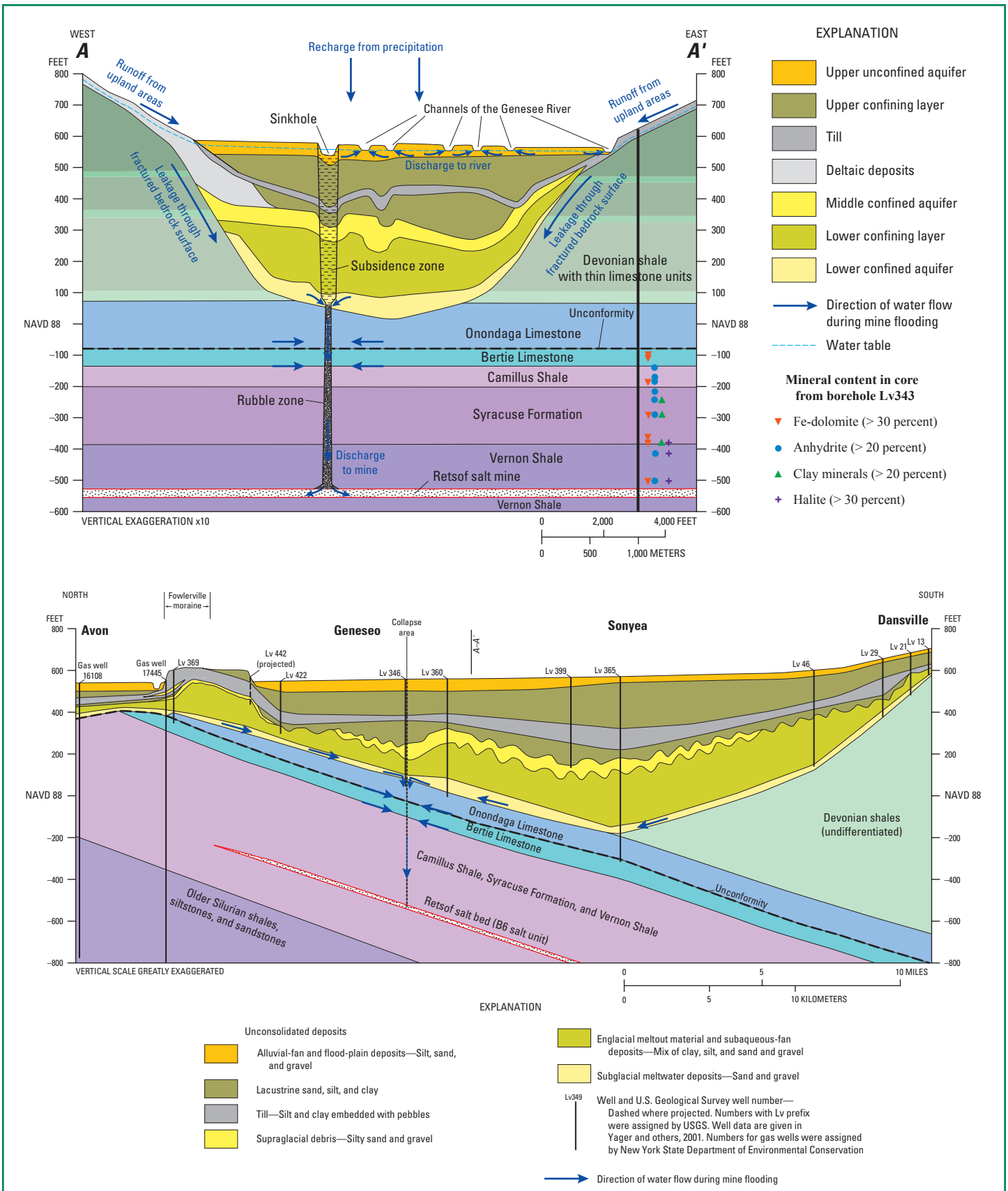



**Figure 2.** The upper stratigraphic cross-section *A–A′* shows one rubble chimney above the collapsed ceiling and the directions of groundwater flow into the Retsof salt mine, Livingston County, New York. The map view of the location of cross section *A–A′* is shown in figure 1 (from Yager and others, 2009, fig. 2). The lower cross section shows a view from north to south under the valley from Avon to Dansville, New York (see fig. 1), describing the unconsolidated deposits and direction of water flow in the lower confined aquifer during mine flooding.

## Effects of Mine Flooding

The flooded salt mine lies beneath a glacially scoured bedrock valley that contains the Genesee River in western New York (fig. 1). The mined salt bed is within Silurian shale overlain by nearly 600 feet of Devonian shale and limestone units that underlie a 500-foot-thick glacial aquifer system containing an upper unconfined aquifer, a middle confined aquifer, and a lower confined aquifer (LCA). These aquifers are separated by thick confining layers (fig. 2).

Deformation of the overlying bedrock layers after the collapse resulted in land-surface subsidence that ranged from 15 feet over some parts of the mine to more than 70 feet above the rubble chimneys. As much as 0.8 feet of subsidence occur south of the mined area as a result of dewatering and compaction of fine-grained sediment in the confining layers of the glacial aquifer system. Two sinkholes that appeared over the rubble chimneys in April and May of 1994 each measured 200 feet in diameter and deepened as surficial sediment subsided into the sinkholes. The subsidence also damaged nearby structures, including a State highway bridge. Dissolution of salt pillars within the flooded mine increased the rate of mine-cavity closure and resulted in continued land subsidence that ranged from 1 to 16 feet over several parts of the mine (subsidence survey map shown on page 9).

Borehole geophysical surveys and drilling in the limestone units in April 1994 and March 2004 indicated that water in the bedrock units above the mine was initially flowing toward the rubble chimneys through two main horizontal fracture zones, and that the collapses had caused increased fracturing within these zones. These zones are designated the O/B fracture zone between the Onondaga and Bertie Limestones and the B/C fracture zone between the Bertie Limestone and the Camillus Shale (fig. 4). A less extensive Syr fracture zone is also present in the upper part of the Syracuse Formation.

Groundwater levels recovered and the hydrostatic pressure within the mine increased, thereby slowing the rate of land subsidence to less than 0.8 inches per year by 2006. After the mine was flooded, saturated halite brine was displaced from the mine by the weight of the overlying material. The only outlet for displaced brine is upward through the rubble chimneys, although some brine could be diverted laterally into the bedrock fracture zones above the mine (fig. 4).

Photograph by Richard Young, Geological Sciences, State University of New York Geneseo, March 1995

An Earth fissure ruptures a field above the western edge of the mine, northwest of 2-Yard South sinkhole. The field surrounding the fissure had subsided almost 1 foot.

Photograph by William Kelly, New York State Geological Survey, April 1996

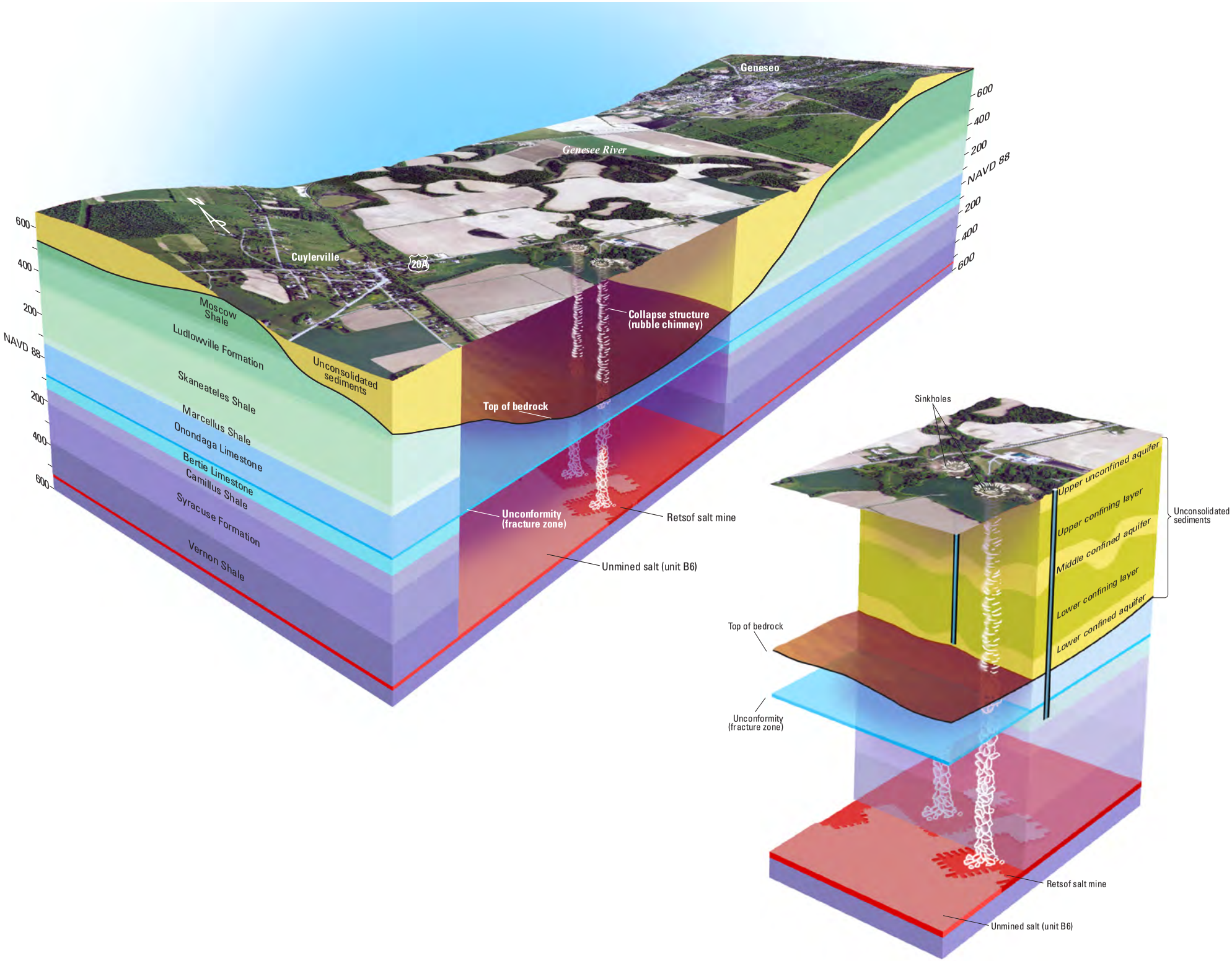
U.S. Route 20A bridge and utilities in April 1996 showing effects of surface subsidence.

## Modeling Studies

The chemistry of groundwater in the collapse area reflects the hydraulic and chemical processes that have occurred since mine flooding began in 1994. Geochemical models were developed to assess the sources of salinity (the flooded mine and the fracture zones within the overlying bedrock units) and to predict whether groundwater-quality changes induced by pumping would lead to mineral dissolution and additional land subsidence. Variable-density flow models were developed to (1) calculate the rates and directions of groundwater flow, (2) assess the effectiveness of mitigation pumping (from 2006 through 2008) in preventing migration of brine into the LCA and (3) predict the lateral extent of potential brine migration within the LCA if the pumping were terminated.

### Geochemical Models

Geochemical models for seven water samples in the collapse area were developed through PHREEQC (Parkhurst and Appelo, 1999) to analyze the variation in chemical composition of water in the collapse area and identify the mixing proportions of waters from three sources—halite brine from the flooded mine, saline water from the overlying bedrock units, and freshwater from the LCA. The models also were used to identify reactions between water and rock that explain the observed water chemistry in the collapse area. Additional geochemical models were used to assess the potential for mineral dissolution and land subsidence caused by the mixing of saline water and brine in the collapse area as induced by brine-mitigation pumping.


Geneseo
Genesee River
Cuylerville
20A
600
400
200
NAVD 88
200
400
600
Moscow Shale
Ludlowville Formation
Skaneateles Shale
Marcellus Shale
Onondaga Limestone
Bertie Limestone
Camillus Shale
Syracuse Formation
Vernon Shale
Unconsolidated sediments
Top of bedrock
Collapse structure (rubble chimney)
Unconformity (fracture zone)
Retsof salt mine
Unmined salt (unit B6)
Sinkholes
Upper unconfined aquifer
Upper confining layer
Middle confined aquifer
Lower confining layer
Lower confined aquifer
Unconsolidated sediments
Top of bedrock
Unconformity (fracture zone)
Retsof salt mine
Unmined salt (unit B6)

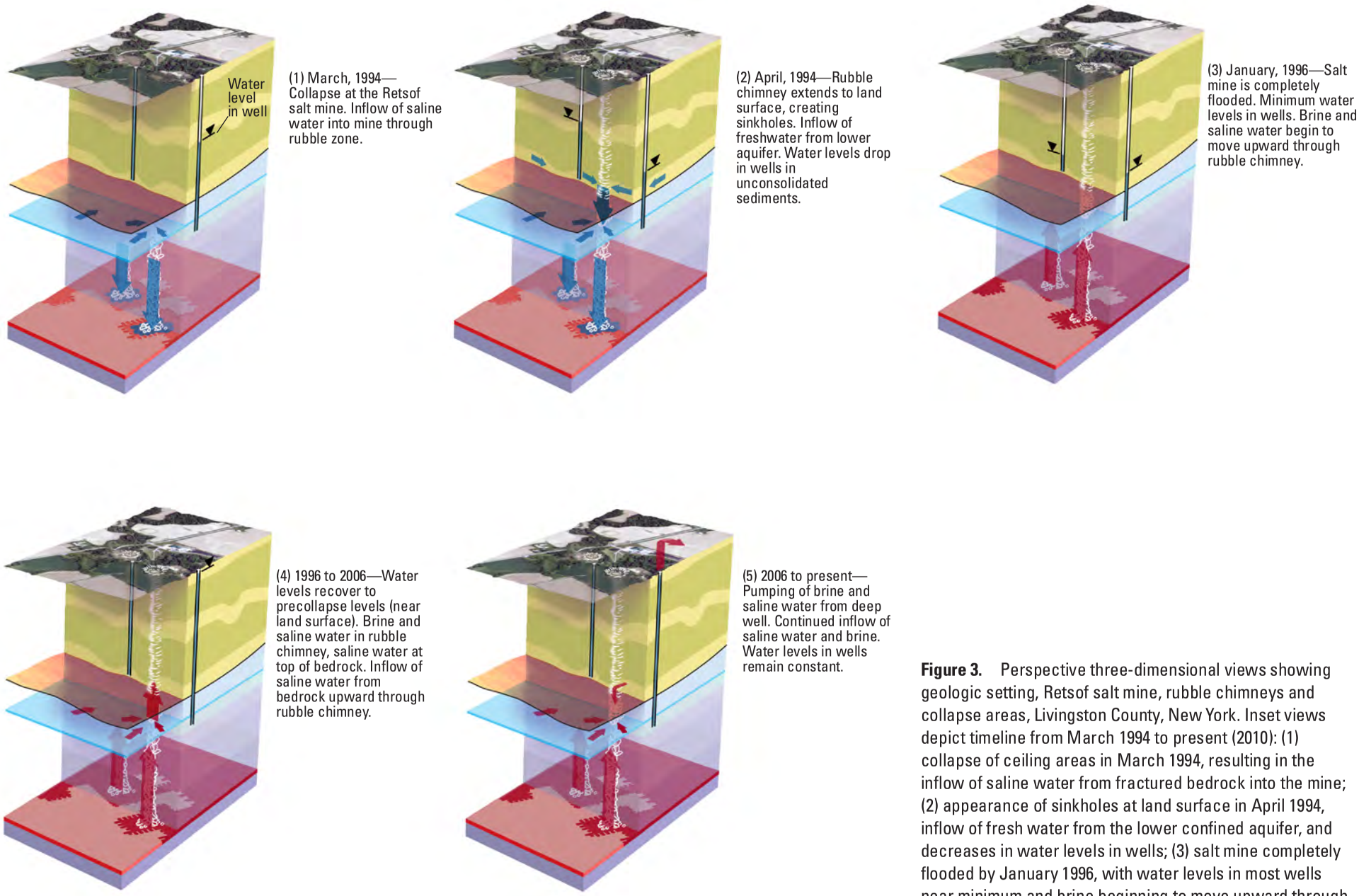



**Figure 3.** Perspective three-dimensional views showing geologic setting, Retsof salt mine, rubble chimneys and collapse areas, Livingston County, New York. Inset views depict timeline from March 1994 to present (2010): (1) collapse of ceiling areas in March 1994, resulting in the inflow of saline water from fractured bedrock into the mine; (2) appearance of sinkholes at land surface in April 1994, inflow of fresh water from the lower confined aquifer, and decreases in water levels in wells; (3) salt mine completely flooded by January 1996, with water levels in most wells near minimum and brine beginning to move upward through the rubble chimneys; (4) recovery of water levels and continuing flow of saline water and brine upward through rubble chimneys from 1996 through 2006; and (5) operation of the brine mitigation project, including the pumping of saline water and brine from deep wells, from 2006 to present.

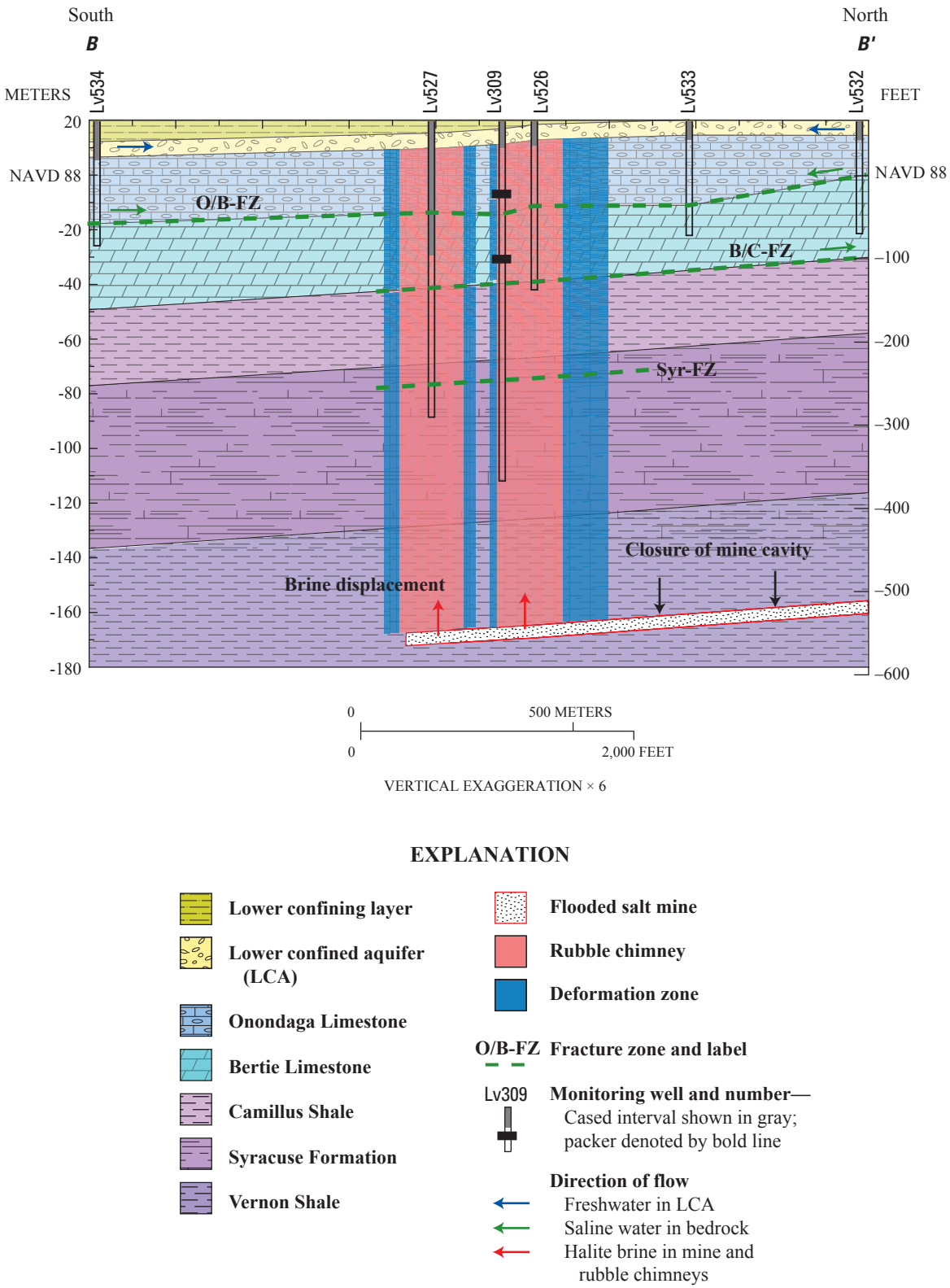



**Figure 4.** Stratigraphic cross-section B–B′ showing rubble chimneys, the deformation zone in the collapse area above the flooded salt mine, and the direction of groundwater flow during water-level recovery, January 1996 through August 2006. Water flows toward the collapse area from the lower confined aquifer and the fracture zone (FZ) between the Onondaga and Bertie (O/B) Limestones. Brine from the mine is displaced upward into the chimneys by closure of the mine cavity. Location is shown in figure 1. From Yager and others, 2009, fig. 7. B/C-FZ, fracture zone between Bertie Limestone and Camillus Shale; NAVD 88, North American Vertical Datum of 1988.

The results of the simulations indicated that the halite brine in the flooded mine is a mixture of aquifer water (81 percent), bedrock water (16 percent), and bromide-rich brine (3 percent) assumed to have formed following deposition of the salt during the Silurian Period. The halite brine from the mine cavity has become diluted with bedrock water as it flows upward through the rubble chimneys, whereas the saline water above the O/B fracture zone is a mixture of saline bedrock water and aquifer water—an indication that brine from the flooded mine had not reached the LCA in 2006. The geochemical models indicated that land subsidence in the collapse area through anhydrite dissolution would not occur under prepumping (2005) conditions, and that subsidence through dissolution could occur but would be unlikely if pumping were kept at a lower rate than the upward flow of halite brine from the mine.

## Groundwater-Flow Models

Analytical and numerical models were used to simulate the movement of aquifer water, bedrock water, and halite brine within the rubble chimneys and the surrounding deformation zones during the 10.7-year period of water-level recovery that followed the period of mine flooding (January 1996 through August 2006). Several one- and three-dimensional (1D and 3D) models were constructed through SEAWAT (Langevin and others, 2007), which simulates flow and solute transport.

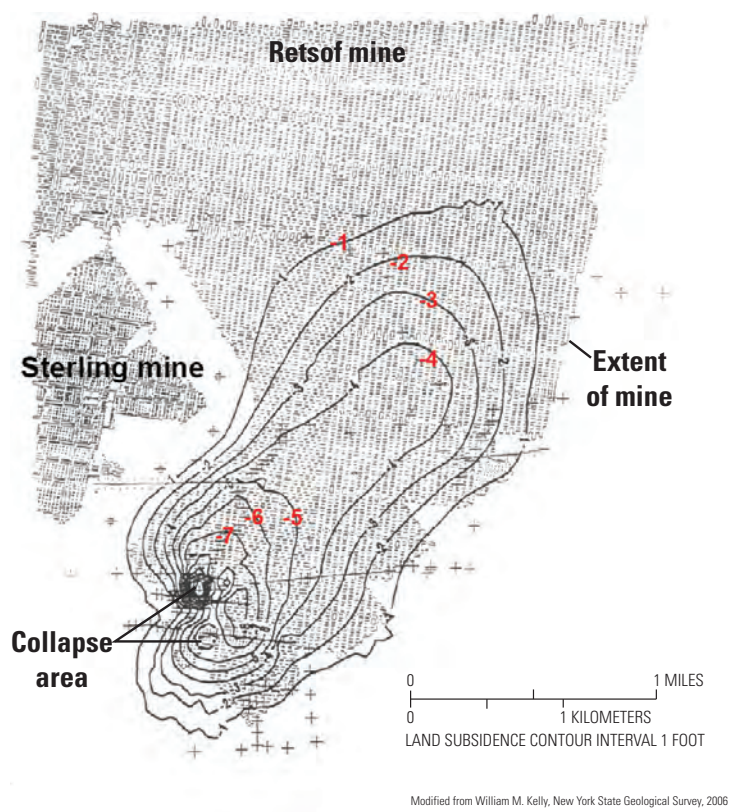
The 1D models were used to simulate upward flow of brine to the LCA through a single rubble chimney to (1) obtain an estimate of the rate of upward brine migration and the longitudinal dispersivity of the rubble material and (2) indicate the number of model layers needed for the 3D simulations, which were designed to predict the movement of the transition zone between saline water and brine during the 10.7-year water-level-recovery period.

The 3D models simulated flow through both rubble chimneys and the surrounding deformation zone and represented the mixing of brine with bedrock water where fracture zones intersected the rubble chimneys. These models were used later to simulate the movement of aquifer water, bedrock water, and mine water in response to mitigation pumping from the collapse area that began in September 2006.

The 3-D models, which represented 1.8-square-mile areas surrounding the rubble chimneys, were each divided into 75 rows and 52 columns, with cell dimensions ranging from 33 feet to 980 feet (fig. 5). The final model had 159 layers and 238,558 active cells. The layers represent the regional bedrock dip from north to south, parallel to the flooded salt mine, with layer spacings that ranged from 13 ft in the bottom half of the domain to 2 ft in the upper half.

Two nearly identical 3D models (models A and B) were constructed to assess the hypothesis that salinity in the upper part of the profile is derived from the inflow of bedrock water from the limestone units, as indicated by the geochemical models, rather than from brine from the mine. Model A represented only fracture zone O/B, whereas model B represented three fracture zones: O/B, B/C, and Syr, as indicated by the observed salinity profile. The thickness and elevation of the fracture zones were interpolated from well borings and borehole geophysical logs. Simulations by the two models gave similar results, but differed slightly in the predicted composition of waters in the collapse area and in the values of some estimated model parameters.

A 1-day steady-state simulation with constant heads in the LCA and the flooded mine provided an initial head distribution for the transient-state simulation of the 10.7-year water-level recovery. The initial conditions were as follows: the mine was filled with brine; the LCA, the rubble chimneys, and the deformation zone were filled with freshwater; and the bedrock fracture zones were filled with saline water. The initial concentration of halite (halite saturation) of water in the rubble chimneys and deformation zone was specified as zero, and a constant saturation of 100 percent was specified for the bottom model layer (flooded mine). Constant heads were specified for each year during the 10.7-year recovery period according to those measured in the LCA. Injection of brine at 100-percent saturation was applied at the bottom model layer to represent brine being displaced from the flooded mine. The brine-displacement rates were estimated through model calibration and were decreased from 110 gal/min at the beginning of the simulation to 25 gal/min at the end. These rates were consistent with the mean rate that was estimated through subsidence surveys during 1996–2001.




Land subsidence near the Retsof mine collapse area, in feet, from April 1995 to July 1996. Dissolution of salt pillars within the flooded mine increased the rate of mine-cavity closure and resulted in continued land subsidence that ranged from 1 to 16 feet over several parts of the mine. After the mine was flooded, saturated halite brine was displaced from the mine by the weight of the overlying material continuing to close the mine cavity. The only outlet for displaced brine is upward through the rubble chimneys, although some brine could be diverted laterally into the bedrock fracture zones above the mine (fig. 4).

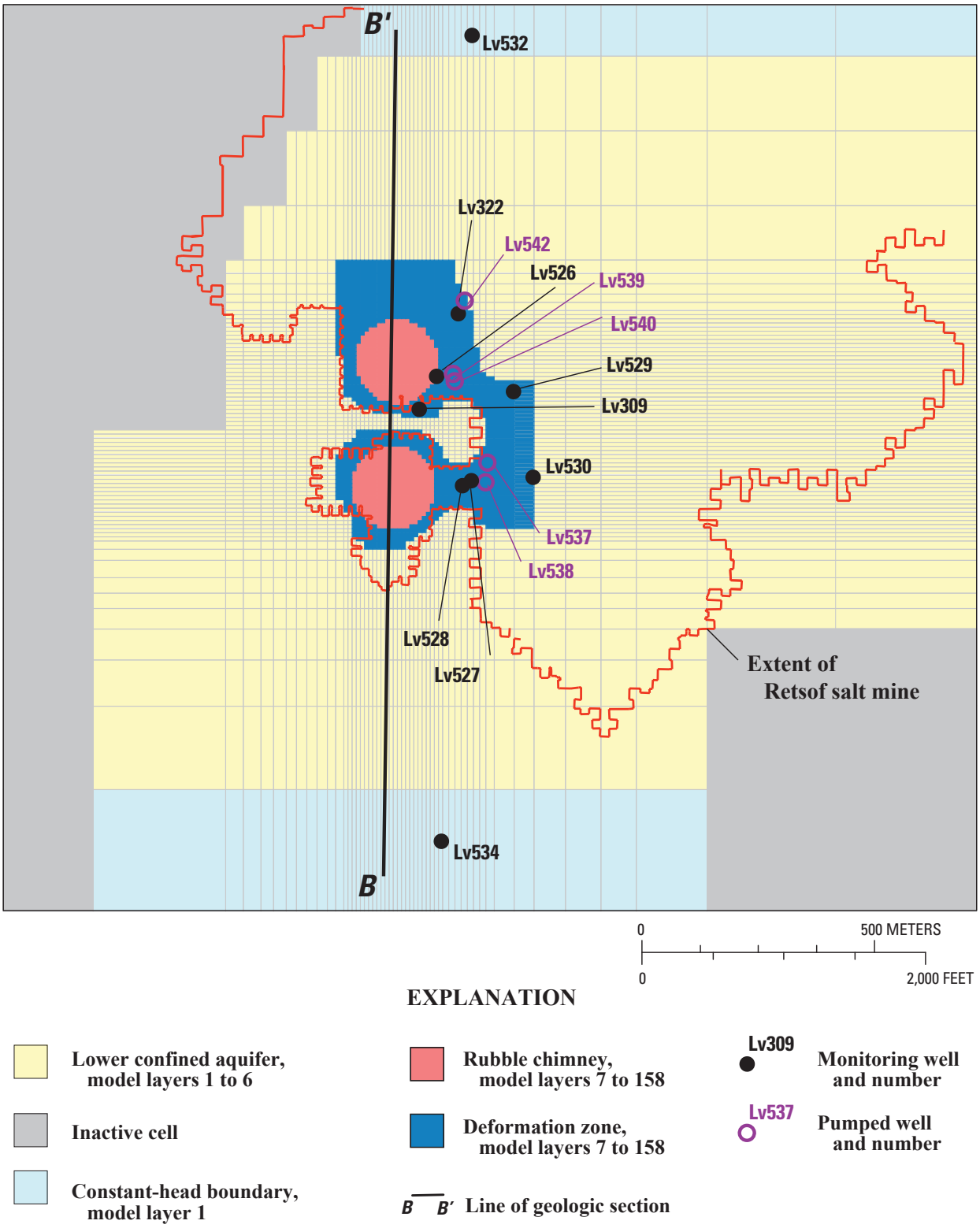



**Figure 5.** Three-dimensional model domain with the extent of the salt mine and the locations of the stratigraphic cross-section B–B′, the lower confined aquifer, the rubble chimneys, the deformation zone, and pumped and monitoring wells. From Yager and others, 2009, fig.16.

### Model Calibration

Both 3D models were calibrated through trial and error to match measured values of halite saturation in time-series plots and a salinity profile based on measurements made in September 2006. The models were intended to illustrate processes that control solute transport rather than to provide calibrated representations of the flow system. Values for hydraulic conductivity, percent porosity, and longitudinal dispersivity were specified for the LCA, the rubble chimneys, the deformation zone, and the three fracture zones. The models were most sensitive to rubble-chimney porosity, which determined the velocity of brine migration and the depth referenced to the North American Vertical Datum of 1988 (NAVD 88), of the transition zone between brine and saline water at the end of the 10.7-year simulation. Different porosity values were estimated for model A (10 percent) and model B (6 percent) to match the salinity profile. The mean inflow rates of groundwater into the collapse area from the O/B fracture zone during the 10.7-year recovery period also differed (30 gal/min and 16 gal/min for models A and B, respectively.

### Simulation Results

Time-series plots and block diagrams were generated to depict (1) the progression of halite saturation; (2) changes in directions of groundwater flow and in proportions of mine water, bedrock water, and aquifer water at selected elevations; and (3) flow directions in and around the rubble chimneys and fracture zones as closure of the mine cavity forced mine water upward into the rubble chimneys and the fracture zones during 1996–2006 (fig. 6). Model B predicted a lower rate of saline-water inflow from the O/B fracture zone than model A and indicated that mixing of waters from the other two fracture zones transported mine water higher in the water column than in model A. Both models indicated lateral diversion of brine into the B/C fracture zone. Model B also indicated possible intrusion of mine water into the LCA. Although the geochemical simulation results do not support this interpretation, it could be valid if parts of the aquifer that were not sampled contained mine water.

Neither model A nor model B indicated that saline water had migrated laterally beyond the collapse area within the LCA. The origin of salinity in the upper part of the collapse area in model A (only one fracture zone) is consistent with results from the geochemical models, whereas the origin of salinity in model B (three fracture zones) indicates movement of mine water into all three fracture zones and is consistent with original predictions from the 1995 geotechnical studies (John T. Boyd Company, 1995) and borehole flow-meter surveys. Whether model A or model B more accurately represents conditions in the collapse area is unknown because the lateral extents of the fracture zones beyond the collapse area are not well delineated and because the boundary conditions specified for the mine and fracture zones are uncertain. As a result of these and other uncertainties, both models may not accurately represent flow and transport in the collapse area. The results, however, provide a description of the major processes and groundwater sources that contributed to the migration of brine and saline water—namely, the advection and dispersion of brine through the rubble chimneys and deformation zones—and the mixing of brine with saline water from fracture zones.

### Simulated Effects of Mitigation Pumping During 2006–11

Models A and B were used to predict the changes in water levels and halite saturation that could be caused by the simulated pumping of the five brine-mitigation wells from September 2006 through August 2011 (fig. 5). Simulated results were compared with changes in water levels and halite saturation induced by pumping during 2006–08 and with the total mass of halite produced by the desalination plant. Both models simulated the movement of mine water, bedrock water, and aquifer water, and also the composition of water produced by each of the pumped wells.

The mitigation-pumping simulations by both models indicated that the current rate of pumping (25 gal/min) will cause halite saturation in the collapse area to decrease and also will alter the directions of groundwater flow; this in turn will halt the upward migration of brine and saline water toward the LCA. The 5-year simulations indicated that the rate of brine displacement from the flooded mine is currently (2009) 25 gal/min or less and that as much as 5 gal/min is possibly being diverted laterally into the B/C fracture zone.

Results of simulations with model B (three fracture zones) matched the halite saturation of the influent to the desalination plant, the amount of halite produced, and the observed decline in saturation through time better than model A (one fracture zone). Both sets of simulations reflected some of the actual conditions in the collapse area, but only simulations by model B indicated that more than one fracture zone affects the migration of saline water and mine water in the collapse area. The actual amount of mixing and rate of flow from the fracture zones, however, could be less than indicated by model B.

A sensitivity analysis with both models identified the parameters to which the simulation results were most sensitive. The results indicated that the principal controls on saturation and water levels were the rates of brine displacement from the mine and the pumping rate, and that the simulated rate of brine displacement could be slower than the actual rate because the simulated declines in saturation were smaller than those observed at most wells from September 2006 through February 2008.

## Implications for Future Mitigation Efforts

The simulations of water-level recovery (1996–2006) indicate that saline water has probably not moved laterally beyond the collapse area within the LCA. The simulations of pumping (2006–08) indicate that pumping has halted the upward migration of brine and saline water and that salinity within the upper parts of the rubble chimneys and deformation zones will decrease over the next few years if the current rates of pumping (25 gal/min) are maintained.

### Effects of Permanent Shutdown

Additional 10-year simulations were conducted to predict changes in halite saturation within the O/B fracture zone and the LCA if the brine-mitigation project had been halted in September 2008 after 2 years of pumping. Results of the simulations of a permanent shutdown with model A indicated that, in the absence of pumping, saturated brine would rise nearly to the O/B fracture zone in 3 years by September 2011 and extend laterally throughout the O/B fracture zone within the

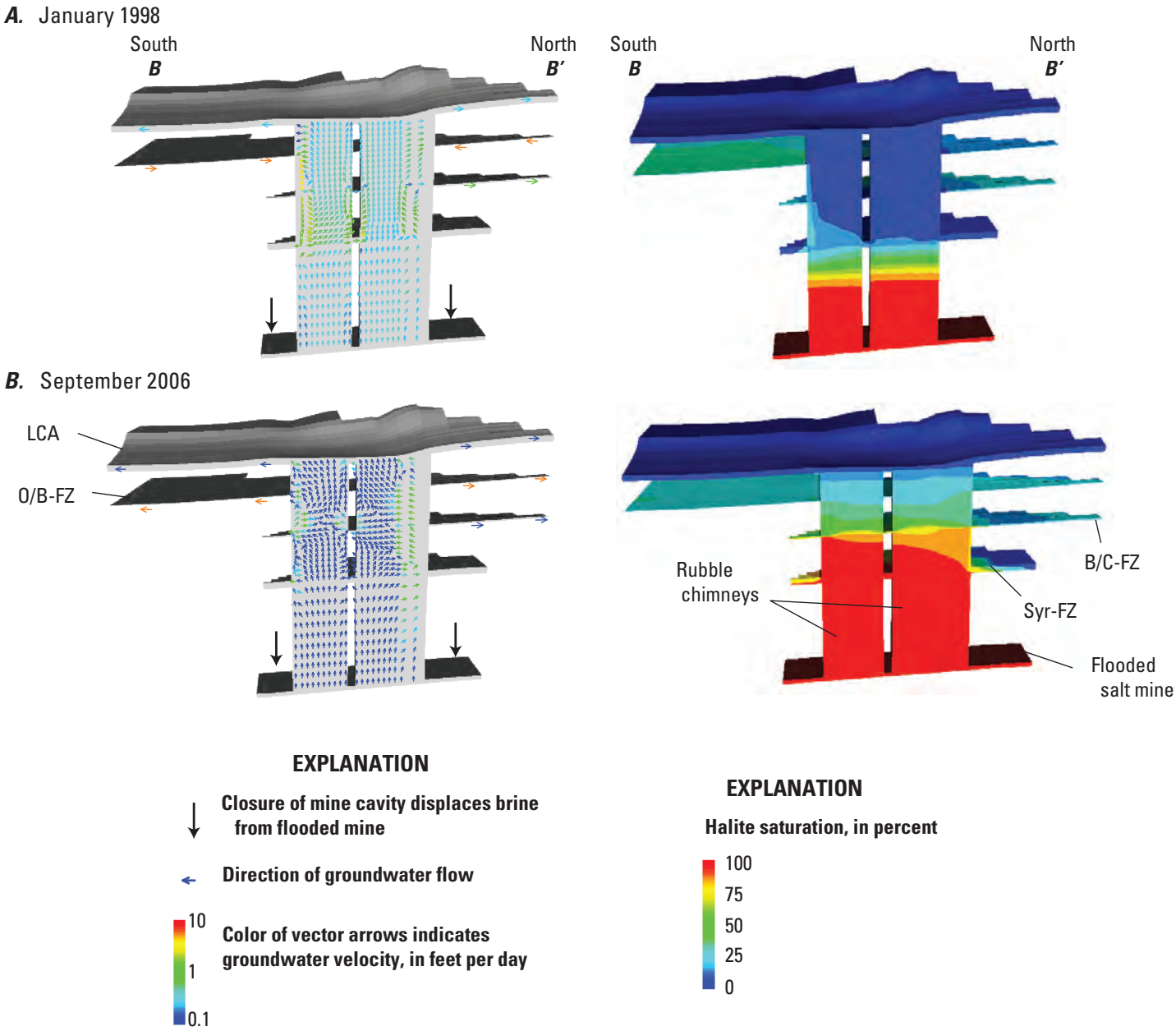



**Figure 6.** Examples of block diagrams along cross-section B–B′ in collapse area showing results simulated by model B for changing directions of groundwater flow (left) and changes in the spatial distribution of halite saturation (right) for *A,* January 1998 and *B,* September 2006. The simulation results indicate groundwater-flow exiting the rubble chimney to both the lower confined aquifer and the Bertie-Camillus fracture zone (B/C-FZ) from January 1998 to September 2006, and a reversal in groundwater-flow direction along the Onondaga-Bertie fracture zone (O/B-FZ), initially as an inflow, but then becoming an outflow. The halite saturation results indicate increased levels of halite saturation in the chimneys and intersecting fracture zones (for example, the Syracuse fracture zone (Syr-FZ)), as brine is displaced from the mine cavity and moves upward. Saline water was detected in the confined aquifer in 2002. Animations of model simulation results can be seen at http://ny.water.usgs.gov/projects/Coram/seawat/seawat.html. Location of section B–B′ is shown in figure 5. From Yager and others, 2009, (fig. 20).

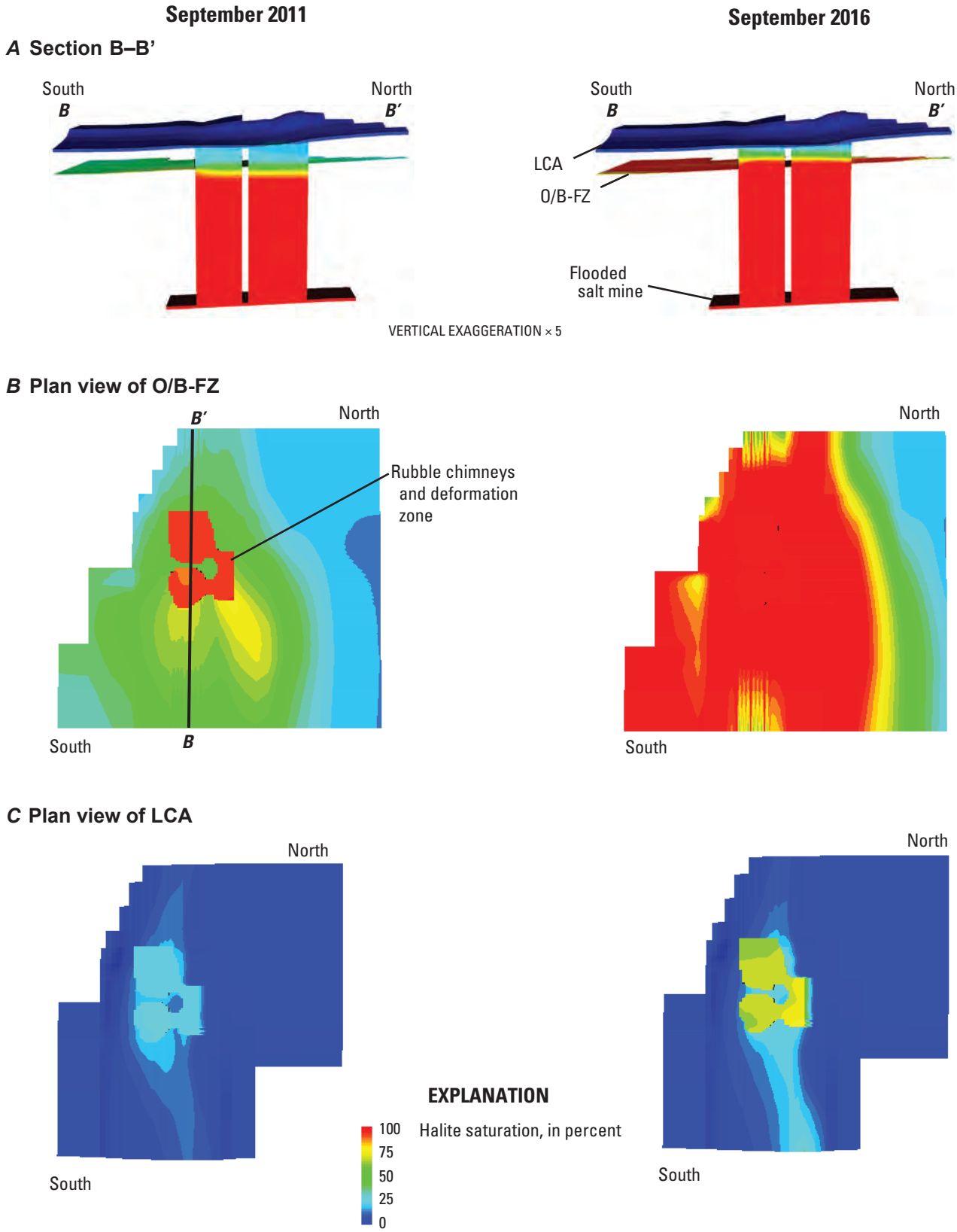



**Figure 7.** Simulated halite saturations in 2011 and 2016 following shutdown of brine-mitigation project after 2 years of pumping from September 2006 through August 2008: *A,* Along cross-section B–B' through the collapse area, the brine would rise nearly to the Onondaga-Bertie fracture zone (O/B-FZ) by September 2011 and spread throughout the zone by September 2016; *B,* plan view of the O/B-FZ indicates that halite brine would fill the rubble chimneys and deformation zone by September 2011 and most of the modeled area of the zone by September 2016; and *C,* the plan view of the lower confined aquifer indicates that the halite saturation would increase to about 75 percent in the rubble chimneys and deformation zone by September 2016 and that a plume of saline water about 25 percent saturated would migrate southward along the sloping bedrock surface of the aquifer toward its lowest point, which is near Sonyea (figs. 1 and 2).

Photograph by Samuel Gowan, Alpha Geoscience, February 2007

The brine-mitigation project, implemented in 2006, has stopped the upward migration of brine and saline water within the collapse area. Pumping brine and saline water from 5 deep wells (fig. 5), the desalination plant is capable of processing 100 gallons per minute of saturated brine, producing potable water and salt.

model domain in 8 years by September 2016 (fig. 7). The brine would continue to rise within the rubble chimneys and enter the LCA, whereupon a plume of saline water would migrate southward along the sloping bedrock surface. The predicted halite saturation would be about 10 percent at the southern model boundary (0.5 mile south of the collapse area) by 2011 and 20 percent by September 2016.

Decreasing the estimated hydraulic conductivity of the O/B fracture zone from 50 feet per day to 25 feet per day decreased the predicted flow of saturated brine into the O/B fracture zone and increased the percent saturation in the LCA. This decrease in hydraulic conductivity would cause predicted saturation at the southern model boundary to increase to 30 percent by September 2016.

Interpretation of the simulation results indicates the following:

» Cessation of pumping would allow saline water from bedrock to flow upward toward the LCA through the rubble chimneys. Halite brine from the mine would eventually reach the LCA.
» Dense saline water that reaches the LCA through the rubble chimneys would migrate southward along the sloping bedrock surface to its lowest point, which is near Sonyea (figs. 1 and 2).
» A pool of saline water would form in this location along the LCA and then extend northward and southward as the flow continues; however, the high relative density of the saline water would probably prevent it from rising into overlying aquifers or to the land surface in that location.
» The fate of mine water (brine) that enters the bedrock fracture zones is uncertain. Some might emerge updip to the north near Avon, where the subcrop area of the Bertie Limestone intersects the bedrock surface (fig. 2). The traveltime, however, cannot be calculated from information available.

### Cost/Benefit Considerations for Continued Aquifer Protection

The LCA is not currently used as a source of fresh water except for a few residential wells southwest of Avon (fig. 1). The estimated volume of water within the aquifer (37 billion gallons) is about 2.5 times the volume of brine expected to be displaced from the flooded mine; therefore, intrusion of saline water and brine into the aquifer can be expected to substantially increase the salinity of aquifer water and render it unusable as a source of supply.

The potential yield of the LCA is 3 million gallons per day, as estimated by steady-state simulations with the model of the glacial aquifer system developed by Yager and others (2001). The value of this resource represents its potential utility as a storage reservoir in addition to the volume of water it could provide.

The brine-mitigation project, implemented in 2006, can be considered a success because the pumping has stopped the upward migration of brine and saline water within the collapse area, and because the desalination plant produces potable water and salt that can be offered for sale. The value of these products is less than the cost of the plant operation, however (S.W. Gowan, Alpha Geoscience, oral commun., 2008).

The protection of the aquifer from the continuously rising brine from the flooded mine would necessitate continued pumping and operation of the desalination plant for the next several hundred years (John T. Boyd Company, 1995). The decision as to whether to continue operation of the plant will therefore probably depend on comparing the costs of mitigation against the present and future value of the groundwater resource.

## Suggestions for Further Research

Continued data collection could allow model refinement and improved assessment of whether continued pumping and desalination are warranted. The following efforts could provide information vital to refine the model and improve the predictions of saline water and brine migration:

» Continued monitoring of the halite saturation of groundwater within the collapse area and fracture zones in the bedrock in response to pumping
» Drilling of additional test holes into the Syracuse Formation outside the collapse area to delineate the extent and hydraulic properties of the bedrock fracture zones, provide additional access points for groundwater sampling, and thus monitor the lateral movements of saline water from bedrock and brine from the mine
» Measurement of groundwater levels in the fracture zones with which to calculate the hydraulic gradients needed for refinement of the boundary conditions specified in model simulations
» Borehole flowmeter surveys during remedial pumping to provide information on flow to and from the fracture zones and the hydraulic properties of these zones

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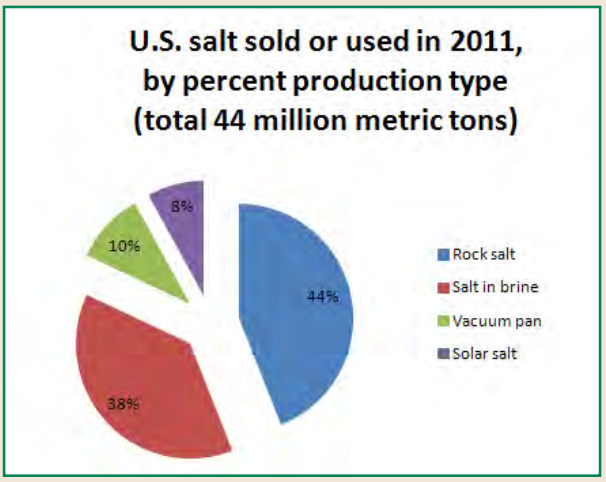
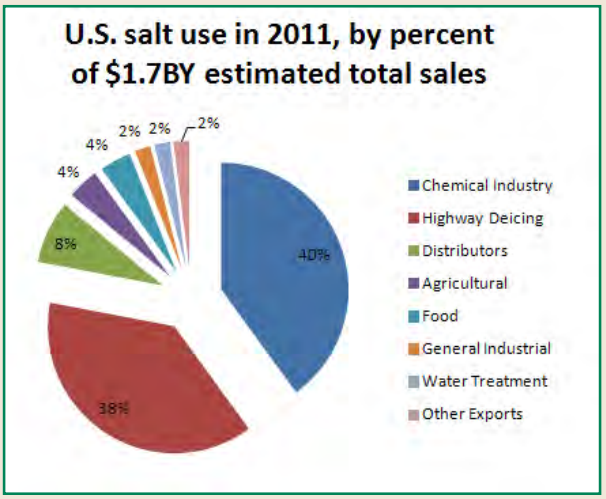
By Richard M. Yager, Todd S. Miller, William M. Kappel, Paul E. Misut, Christian D. Langevin, David L. Parkhurst, and M. Peter deVries


## Selected USGS Reports Related to Salt Production, Brine, and Saltwater Intrusion in New York

- Salt - Statistics and Information (shown right) from USGS National Minerals Information Center, Mineral Commodity Summaries, January 2012 at http://minerals.usgs.gov/minerals/pubs/commodity/salt/.
- The Retsof Salt Mine Collapse—Widespread subsidence occurred after a mine collapse in the Genesee Valley, New York at http://pubs.usgs.gov/circ/circ1182/pdf/14Retsof.pdf.
- Salt production in Syracuse, New York ("The Salt City") and the Hydrogeology of the Onondaga Creek Valley at http://ny.water.usgs.gov/pubs/fs/fs13900/FS139-00.pdf.
- Halite brine in the Onondaga Trough near Syracuse, New York: Characterization and simulation of variable-density flow at http://pubs.usgs.gov/sir/2007/5058/.
- Chloride in groundwater and surface water in areas underlain by the glacial aquifer system, northern United States at http://pubs.usgs.gov/sir/2009/5086/.
- Evaluation of well logs for determining the presence of freshwater, saltwater, and gas above the Marcellus Shale in Chemung, Tioga, and Broome Counties, New York at http://pubs.usgs.gov/sir/2010/5224/.
- Simulation of variable-density ground-water flow and saltwater intrusion beneath Manhasset Neck, Nassau County, New York, 1905–2005 at http://pubs.usgs.gov/sir/2008/5166/.



James Rajotte/The New York Times/Redux

Rock salt being unloaded off of a ship in Oswego, New York, October 2007

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New York Water Science Center
U.S. Geological Survey
30 Brown Road
Ithaca, New York 14850

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