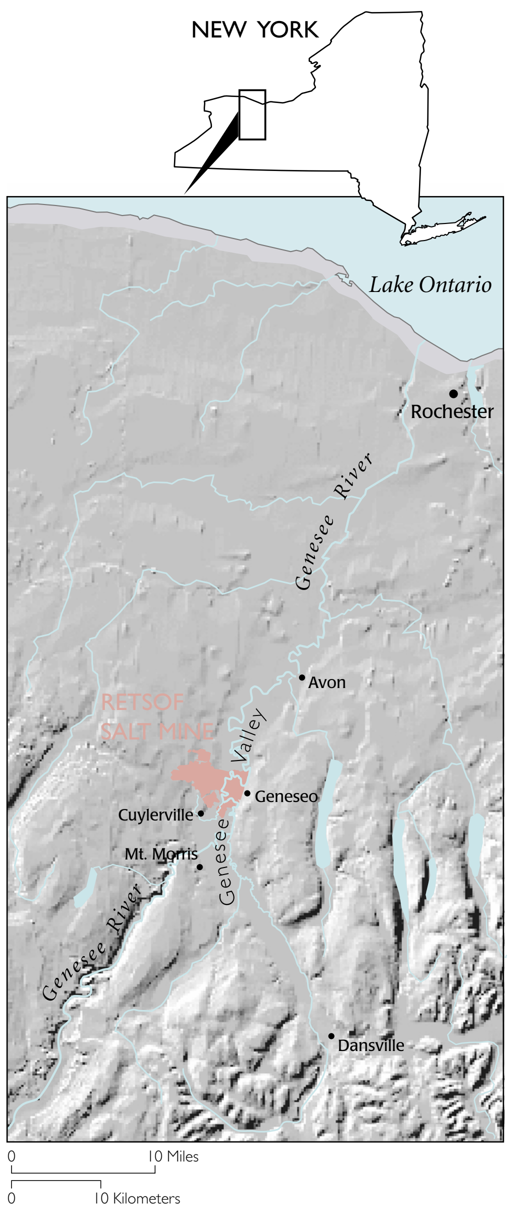
The Retsof Salt Mine Collapse

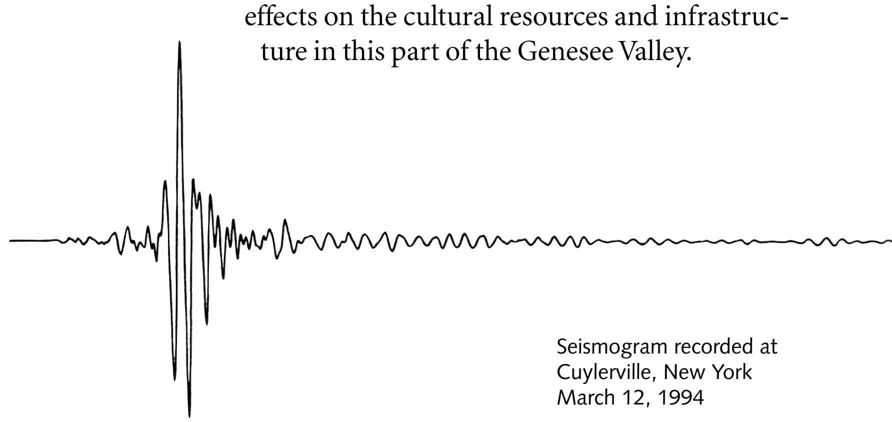
Widespread subsidence occurred after a mine collapse in the Genesee Valley, New York



On March 12, 1994, at 5:43 a.m. (local time), an apparent earthquake of magnitude 3.6 centered near Cuylerville, New York, woke residents and registered on seismographs 300 miles away. Prompted by a call placed from a local resident, the USGS National Earthquake Information Center confirmed that a seismic event had occurred near Cuylerville and immediately notified State emergency services offices in New York who, in turn, notified the Livingston County Sheriff's Department. The Sheriff's Department contacted the Retsof Mine, which, except for some limited subsurface maintenance activity, had suspended active mining that weekend.

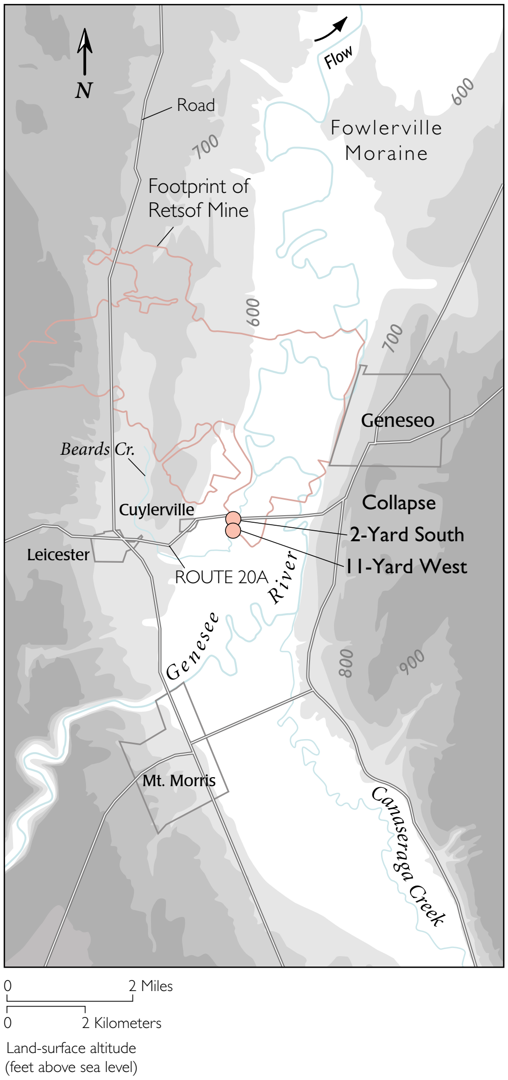
Mine officials discovered that a 500- by 500-foot section of shale roof rock some 1,200 feet below land surface had collapsed in a part of the mine known as room 2-Yard South. Mine officials detected methane and hydrogen sulfide gases, and ground water was flowing into the mine from the roof collapse area at nearly 5,000 gallons per minute.

This collapse began a series of events that would eventually lead to the further collapse and complete flooding of the mine, large declines in local ground-water levels, degradation of potable ground-water supplies, land subsidence, release of natural gases (methane and hydrogen sulfide) to the atmosphere, and other detrimental effects on the cultural resources and infrastructure in this part of the Genesee Valley.



Seismogram recorded at Cuylerville, New York March 12, 1994

William M. Kappel, Richard M. Yager, and Todd S. Miller
U.S. Geological Survey, Ithaca, New York



SALT MINING HAS A LONG HISTORY IN THE GENESEE VALLEY

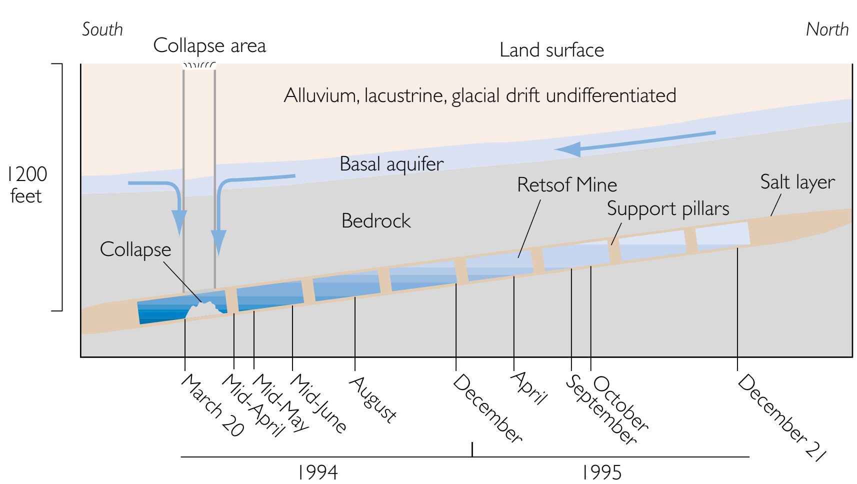
Salt mining (both salt-solution and rock-salt mining) began in the Genesee Valley in the early 1880s, and in 1884 the Empire Salt Company excavated a shaft to extract rock salt from seams 900 feet below land surface. In 1885 the Empire Salt Company was renamed the Retsof Mine Company and the Village of Retsof was founded near the mine shaft. During the next 110 years, the mine grew to become the largest salt-producing mine in the United States and the second largest in the world. Before the initial collapse in March 1994, the mine encompassed an underground area of more than 6,000 acres, and the mine footprint (outer edge of mined area) extended over an area of nearly 10 square miles.

At the time of the collapse, the Retsof Mine was owned by Akzo-Nobel Salt Incorporated (ANSI), and, during the winter of 1993–94, operated at full capacity to meet demands for road salt throughout the northeastern United States. Prior to its closure, the Retsof Mine played a major role in the Livingston County economy, providing more than 325 jobs with an annual payroll in excess of $11 million and estimated annual gross sales of more than $70 million (NYSDEC, 1997). During the 17 months following the collapse, mining operations shifted to the northern, high end of the mine in a race to salvage mineable salt before the mine flooded. The Retsof Mine ceased operations on September 2, 1995, and by December, 21 months after the initial collapse, the mine was completely flooded.

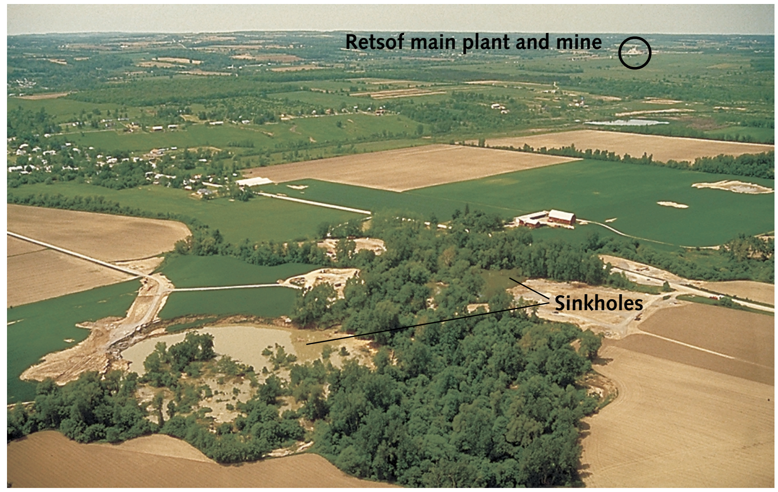
THE COLLAPSE TRIGGERED A SERIES OF LOCAL EVENTS

Four months before the collapse, in November 1993, room 2-Yard South was abandoned because of concerns over large and increasing rates of "convergence" or reduction of the opening between the floor and ceiling of the room. (A new mining technique, "yielding pillar," was used in this area in response to floor buckling and roof collapse, which was occurring with greater frequency in the south-

This cross-sectional schematic shows how water from the basal aquifer entered the mine through the collapsed area. After 21 months the salt mine was completely flooded.



This northwest aerial view shows sinkholes above room 11-Yard West (left foreground) and room 2-Yard South (right center, partially obscured by trees). Circle indicates location of the Retsof main plant area, some 4 miles northwest of the sinkholes.



(Ron Pretzer, LUXE, May 1994)

A sinkhole developed above room 11-Yard West and filled with water from Beards Creek.

(Richard Young, Geological Sciences, SUNY Geneseo, June 1994)

The roadbed of Route 20A was fractured on the east side of the collapsed bridge over Beards Creek. This view is above the room 2-Yard South collapse area looking west, toward the former Hamilton farm house (subsequently purchased by ANSI).

(Richard Young, Geological Sciences, SUNY Geneseo, April 12, 1994)

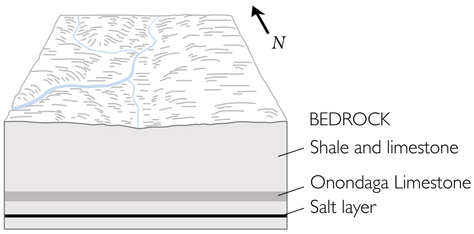
ern end of the mine.) After the March 12, 1994, collapse of room 2-Yard South, ground water flowed into the previously dry mine at a rate of about 7 million gallons per day, dissolving residual rock salt and filling the lowest, downdip levels of the mine with saturated brine. ANSI monitored the concentration of hazardous gases and the encroaching water level in the mine as the shoreline in the mine steadily moved northward.

Local governmental officials had posted warning signs at the Route 20A bridge over Beards Creek the day before the collapse because of small bumps in the pavement on the bridge approach sections. There is some anecdotal evidence that, several days earlier, local travelers had noticed a change in the smoothness of the roadbed near the bridge, suggesting a surface expression of the underground convergence that led to abandonment of room 2-Yard South several months earlier.

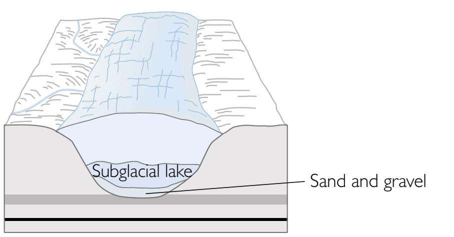
Within days of the collapse, impacts on the glacial and bedrock aquifer systems and on the land surface were reported on an expanding scale. Some homes had sustained structural damage due to the initial earth tremors and, within 1 week of the collapse, residents along Wheelock Road, south of Cuylerville and southwest of the mine, reported that several water wells had gone dry (NYSDEC, 1997). The USGS and the Livingston County Health Department began monitoring ground-water levels and streamflow in the area.

On April 6, a 200-foot diameter by 20-foot deep, cone-shaped sinkhole appeared along the channel of Beards Creek, immediately above the room 2-Yard South collapse zone, just south of the Route 20A bridge. And 2 weeks later, accompanied by additional earth tremors, this sinkhole expanded to about 600 feet in diameter.

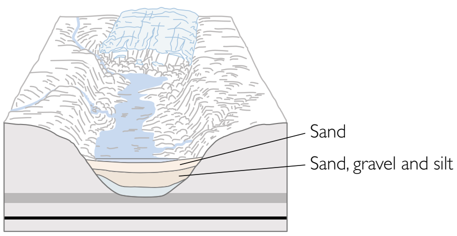
On April 8, seismic events indicated a roof collapse in mine room 11-Yard West, south of and adjacent to room 2-Yard South. Following this collapse, ground-water inflow to the mine increased to about 22 million gallons per day. An expanding sinkhole developed over 11-Yard West on May 25, 1994. The sinkhole was about 50 feet deep, about 200 feet in diameter, and immediately filled with water captured from Beards Creek. Over time this sinkhole grew to about 800 feet in diameter.



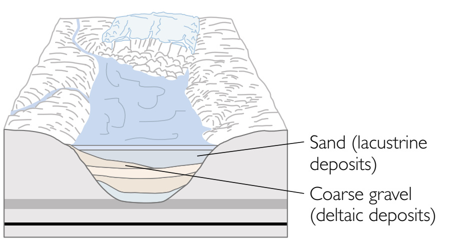
The ancient Genesee River crossed sedimentary rocks.



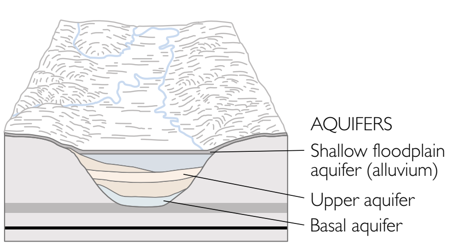
Glaciers scoured the bedrock, leaving a wide, deep valley that did not always follow the course of the Genesee River. At times the glaciers covered the entire area. During periods of glacial retreat, subglacial lakes formed and sediment was deposited.



The periodic retreat and advance of glaciers left behind mounds of debris (moraines) and thick glacial deposits (drift).



During deglaciation a series of proglacial lakes formed that deposited lake (lacustrine) sediments on the valley floor.



After glaciation alluvial (floodplain) gravel, sand, and silt were deposited on top of the glacial sediments.

THE NATURAL HISTORY OF THE GENESEE VALLEY SET THE STAGE FOR WIDESPREAD DAMAGE AFTER THE COLLAPSE

Current knowledge of the occurrence and flow of ground water and the complex stratigraphy of the glacial aquifer system in Genesee Valley is sparse. Prior to the collapse, the hydrogeologic framework of the valley-fill materials had not been investigated in detail. Since the mine collapse, several studies have addressed the hydrogeologic framework (Nittany Geoscience, 1995; Alpha Geoscience, 1996), but insufficient data exist to thoroughly characterize the interconnections among glacial units and bedrock aquifer zones.

The Genesee Valley from Dansville to Avon, New York, includes the Canaseraga Creek Valley and, from Mt. Morris northward, the Genesee River Valley. The valley formed as a result of several geologic processes including the ancestral uplift and stream erosion of gently dipping Paleozoic sedimentary rocks, followed by periods of glaciation in which ice scoured and modified the bedrock topography, leaving behind unconsolidated sediments. Recently, stream erosion and deposition added about 50 feet of alluvium (gravel, sand, and silt) to the glacial sediments.

The unconsolidated glacial sediments that fill the Genesee Valley were deposited during cycles of glacial advances and retreats. Glaciers several thousands of feet thick deepened and widened the valley. About 12,000 years ago the most recent glacier retreated from the valley, leaving behind thick glacial deposits. Where the glaciers paused and the ice melted, mounds of glacial debris, called end moraines, were deposited at the frontal (southern) ice margin. The melting ice produced large volumes of water that transported, sorted, and deposited boulders, gravel, cobbles, sand, silt, and clay and carried these sediments in meltwater streams to the south. Proglacial lakes existed in the glacially-deepened valley between the valley walls and the receding glacier during most of the glacial period.

During deglaciation, outlets low enough to drain the proglacial lakes did not exist until the ice margin was 10 to 12 miles north of Geneseo. During this period, the present Genesee River and Canaseraga Creek watersheds drained to the north, toward the glacier, into a series of progressively lower proglacial lakes. The final and lowest proglacial lake formed when the ice deposited the Fowlerville moraine, which extends from about 4.5- to 8-miles north of the collapse area. Water ponded in the Genesee Valley south of the Fowlerville moraine, depositing lake sediments on the valley floor. Eventually the lake drained as the Genesee River cut a channel in the Fowlerville moraine (Young, 1975). As much as 700 feet of glacially derived gravel, sand, silt, and clay were deposited in a subglacial and glaciolacustrine (glacial lake) environment.

This view shows the Upper Genesee Valley looking east.

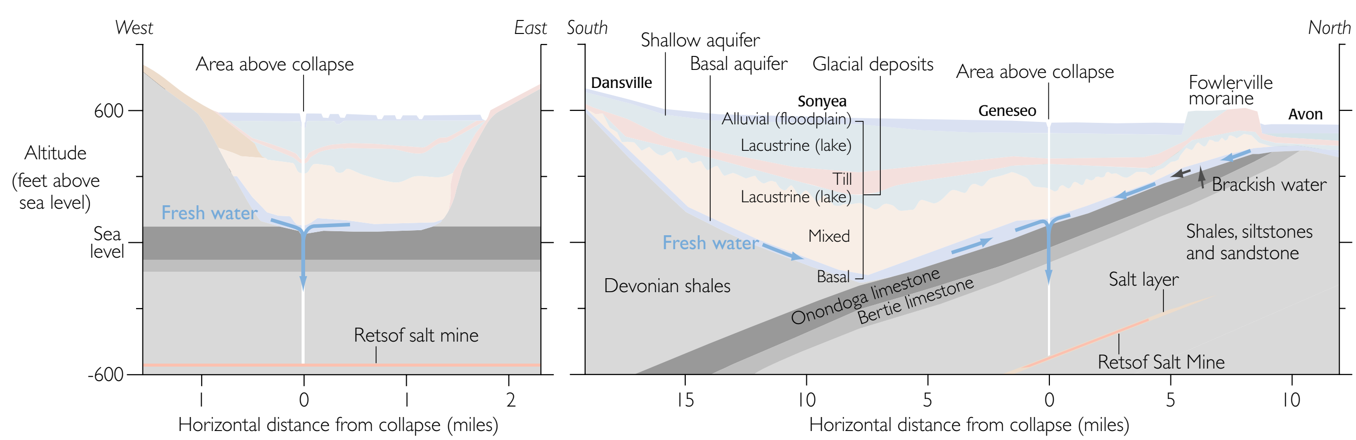
(Richard Young, Geological Sciences, SUNY Geneseo)

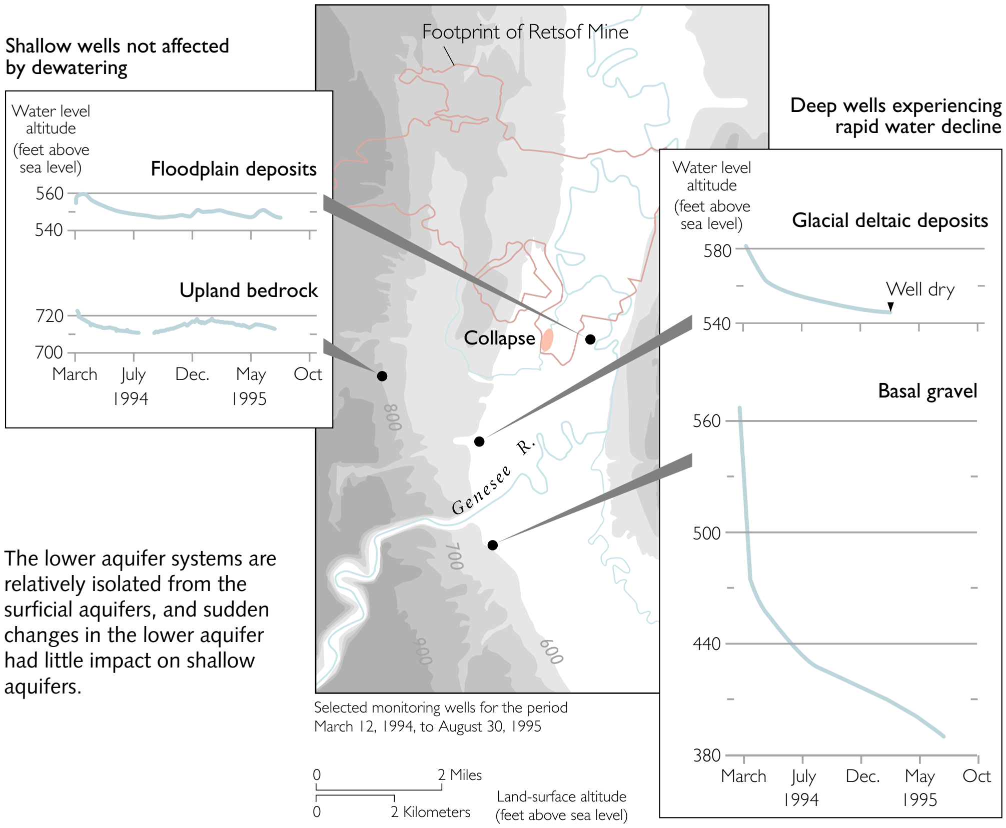
The buried bedrock surface follows the slope of the resistant sedimentary carbonate beds of the Onondaga Limestone, dipping approximately 42 feet per mile to the south. Overlying the bedrock surface is a thickening wedge of glacial valley-fill sediments that ranges from a few hundred feet thick on the north, near the Fowlerville Moraine, to about 750 feet thick in the deepest part of the valley near Sonyea. South of Sonyea, the valley fill thins. Ground water in the glacial deposits and portions of the underlying carbonate bedrock has been the primary source for the inflows to the flooded Retsof Mine. The fine-grained lake silt and clay closer to the land surface form a barrier between the alluvial and deeper glacial aquifers.

Water-bearing zones are found within the fractures and bedding planes near the top of the Onondaga Limestone at the base of the valley fill. Another water-bearing zone is found at the contact between the Onondaga Limestone and the underlying Bertie Limestone. Few valley wells tap bedrock, and the most productive wells completed in the Onondaga and Bertie Limestones seldom produce more than several tens of gallons per minute (Dunn, 1992). The Bertie Limestone subcrops beneath the valley floor north of the Fowlerville moraine, under several hundred feet of glacial sediment, and is generally considered a divide between fresher water above and a more mineralized water below.

The principal aquifer in the valley appears to occur at the base of the valley fill. The relatively thin basal aquifer is composed of sand and gravel deposited on top of the Onondaga Limestone in the central and northern parts of the valley and on top of the low-permeability Devonian shales to the south. The hydraulic connection between the basal aquifer and the underlying bedrock units throughout the valley is poorly understood, but the connection is generally assumed to be better in the northern half of the valley, where the aquifer is in direct contact with the weathered and fractured top of the Onondaga Limestone. Under natural conditions ground water flows upward from the Onondaga to the basal aquifer. Though the basal aquifer is generally overlain by lower-permeability

Water from the basal aquifer entered the mine through the collapsed area.





Selected monitoring wells for the period March 12, 1994, to August 30, 1995

The lower aquifer systems are relatively isolated from the surficial aquifers, and sudden changes in the lower aquifer had little impact on shallow aquifers.

glacial drift, in some areas north of the mine more permeable layers have been reported within the glacial deposits.

Some wells in the valley are completed within the glacial deposits, and some wells completed in the deeper basal aquifer are also screened in the glacial deposits, an indication that there is locally enhanced permeability at intermediate depths. There appears to be a vertical hydraulic connection between the basal aquifer and the permeable zones in the glacial deposits, based upon recent data from ground-water monitoring wells, but the areal extent of these vertically connected zones is unknown.

Shallow ground water occurs in the alluvial deposits found to a depth of 50 feet below the valley floor. The water table in the alluvium is generally less than 15 feet below land surface, and is in hydraulic connection with the Genesee River, Canaseraga Creek, and other tributaries on the valley floor. Other shallow ground water occurs in the Fowlerville Moraine deposits. Most recharge and discharge of the Genesee Valley aquifer system occurs between the Genesee River, its tributaries, and the shallow water-table aquifer in the alluvium (Nittany Geoscience, 1995). Water levels in wells completed in the alluvium were not affected by the mine collapse.

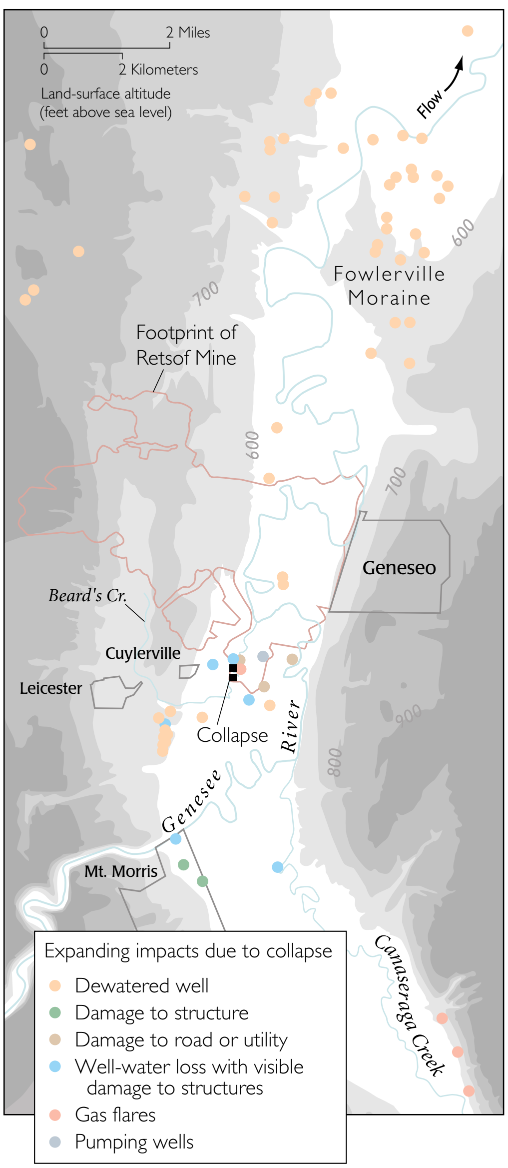
After the mine collapse, most of the inflows to the mine probably came from storage in the basal aquifer and the glacial deposits through the collapse areas above rooms 2-Yard South and 11-Yard

This view of the Genesee Valley floodplain was taken above the southern end of the mine looking southwest.

(Richard Young, Geological Sciences, SUNY Geneseo, 1995)

West. Water levels in wells began declining almost immediately near the collapse zones. Water levels continued to decline rapidly through 1994, and more slowly in 1995, until the mine was completely flooded in January 1996. By then, water levels had fallen more than 350 feet in some wells near the collapse zones. In total, an estimated 42,000 acre-feet of ground water invaded the mine.

The basal aquifer is relatively isolated from surficial sources of recharge and discharge, and changes in the lower part of the aquifer system are not likely to have immediate or significant impact on the shallow sources. However, the rate of ground-water drainage into the mine far exceeded the estimated rate of recharge to the deeper subsurface aquifers, and it is expected that it will take a decade or longer for ground-water levels to recover throughout the aquifer system.



IMPACTS OF THE COLLAPSE WERE OBSERVED MILES AWAY

The effects of the collapse include, but are not limited, to the following:

- Reduced air quality and public-safety issues resulting from the emanation of methane and hydrogen-sulfide gases
- The loss of potable water supplies—both a reduction of quantity and degradation in quality and
- Short- and long-term land subsidence

Natural gas was vented into the environment

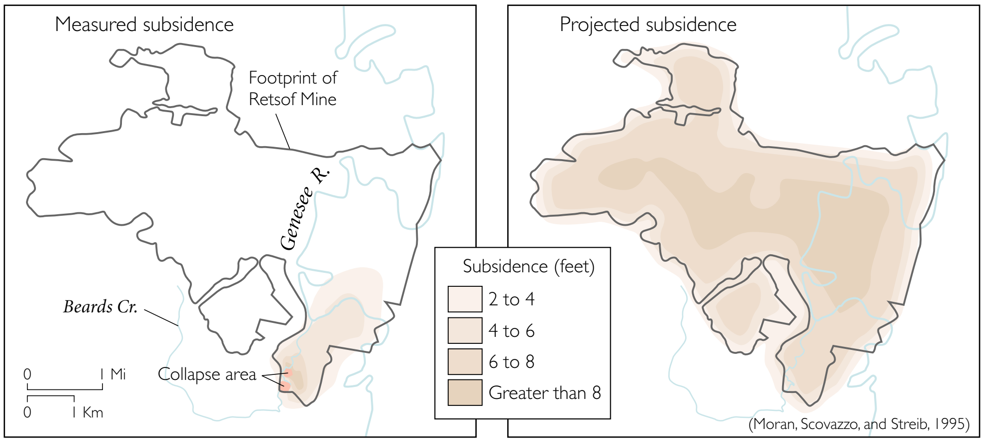
Soon after the mine began to flood and water levels in the basal aquifer were lowered, natural gas in the form of hydrogen sulfide (odor of rotten eggs) and methane (odorless, combustible) began exsolving from ground water—just as carbon dioxide comes out of solution after a bottle of soda is opened. In the area of the collapse, lowered water levels allowed natural gas to escape through test wells drilled near the collapse area and preexisting domestic water-supply wells several miles farther to the southeast. In September 1994 the State Department of Environmental Conservation ordered ANSI to develop a natural-gas monitoring and response plan. By May 1995 the County and State Health Departments required ANSI to flare-off (burn) gas from several collapse-area wells to reduce the odor and protect the health and safety of residents living in Cuylerville and the surrounding area.

Potable water supplies were diminished

Although some shallow alluvial wells near the mine were unaffected, some domestic wells along the margins of the valley and in the deeper zones of the Genesee Valley aquifer system experienced lowered water levels, and some wells went dry. The rate of water-level decline varied: water levels declined 20 feet or more along Wheelock Road (about 1 mile southwest of the mine) within days of the collapse, whereas water levels gradually declined 50 feet or more in the

Local subsidence occurred due to dissolution of salt pillars by freshwater inflow March 1994 to March 1996.

More extensive subsidence due to closure of the salt cavity is projected.



(Moran, Scovazzo, and Streib, 1995)

Fowlerville area (about 6 miles north of the mine) and in Mt. Morris (about 4 miles south of the mine) for 2 years following the collapse. Pursuant to an agreement between ANSI, Livingston County, and the State of New York, ANSI has been supplying water to residents whose wells have gone dry and where water quality has deteriorated.

The effects of ground-water flow to the mine extend more than 10 miles north and south of the collapse area. Following the mine collapse and lowering of ground-water levels, highly mineralized ground water has apparently migrated into freshwater supplies. There are two potential sources: a deep-basin brine that migrates upward along bedding-plane fractures within the Bertie Limestone to the intersection of the Bertie outcrop and the basal aquifer, and a halite (rock salt) component, which may be introduced through older natural-gas or salt-solution wells within the Fowlerville moraine. The mineralized ground water flows downdip (to the south) through the basal aquifer toward the mine collapse area, an apparent reversal of the pre-collapse hydraulic gradient. Presently, salinity is increasing in Fowlerville Moraine wells, south of where the Bertie outcrops and is in contact with the basal aquifer.

A well flares methane and hydrogen sulfide gases from a fracture zone on the eastern margin of the room 2-Yard South sinkhole.

(Richard Young, Geological Sciences, SUNY Geneseo, 1995)

Several types of subsidence were observed

Subsidence damage related to the mine collapse includes:

- The creation of 2 large sinkholes
- The temporary loss of State Route 20A through Cuylerville
- Structural damage to homes and businesses and
- Damage to agricultural lands, public utilities, and cultural resources.

Besides the catastrophic formation of sinkholes over rooms 2-Yard South and 11-Yard West, the damage involves three other types of subsidence, which are important at different scales.

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

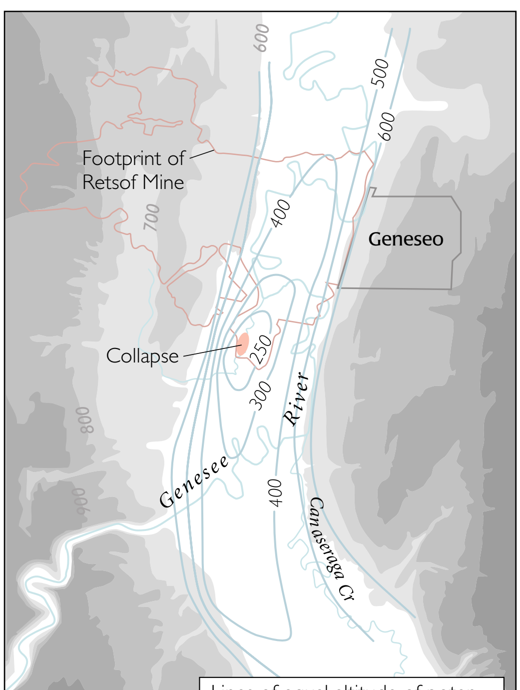
(Richard Young, Geological Sciences, SUNY-Geneseo, March 1995)

The first type of subsidence that normally occurs over any mined-out area is due to the slow closure of the mine opening. Mining engineers expect the land overlying the Retsof Mine footprint to subside about 8 to 9 feet over the next 100 to 200 years (Van Sambeek, 1994). Most of the estimated subsidence is expected to be realized during the next 100 years (Shannon and Wilson, 1997). Differential subsidence is expected along the margins of the mine, where adjacent areas will subside nonuniformly. This creates stresses within the land mass, which may rupture the surface or subsurface. Some horizontal movement of land surface in these areas is expected, as well as some tilting of the land surface toward the mine. Structures located in these regions may continue to be prone to damage as the mine subsidence evolves.

A second type of subsidence seen near the collapse area and farther to the north and east was caused by the flow of ground water into the mine and resultant dissolution of unmined salt. Fresh ground water, less dense than saltwater, entered the mine cavity quickly, and preferentially dissolved the salt along the mine roof. As the mine roof collapsed, it allowed the freshwater to dissolve more salt in the supporting salt pillars and, over time, left large areas without roof support. This type of subsidence evolved rapidly as many salt pillars were quickly dissolved by the large inflow of freshwater, and subsidence in this area was greater and occurred sooner than would be expected for a dry mine situation (Van Sambeek, 1996). When the mine filled with saturated brine, this type of subsidence ceased.

The third type of subsidence to occur in the Genesee Valley is due to the dramatic lowering and anticipated slow recovery of ground-water levels in the confined-aquifer system. This type of subsidence is due to aquifer-system compaction that typically accompanies the depletion of alluvial aquifer systems. The ground-water level declines experienced after the mine-roof collapse—more than 350 feet near the collapse and as much as 50 feet as far as 8 miles away—is sufficient to cause measurable elastic compression of the glacial sediments of the Genesee Valley aquifer system. It is possible that the large stresses imposed on the aquifer-system skeleton by the large drawdowns may have caused some inelastic, and largely irreversible, compaction of aquitards in the Genesee Valley, but

The lowering of water levels in areas beyond the mine footprint may eventually cause aquifer-system compaction and land subsidence.



0 2 Miles
0 2 Kilometers
Land-surface altitude (feet above sea level)

Lines of equal altitude of potentiometric surface, December 1995 (feet above sea level) currently this effect is presumed to be small. Aquifer-system compaction may contribute to land subsidence on a spatial scale larger than the mine footprint, especially in regions where large changes in ground-water levels persist and where the glacial deposits contain an appreciable thickness of fine-grained, more compressible sediments. It is possible that the valley floor may continue to be affected by residual compaction long after ground-water levels have fully recovered in the aquifers (Riley, 1969). An accurate evaluation of the magnitude, timing, and areal extent of land subsidence due to aquifer-system compaction will depend on more detailed knowledge of the hydrogeology of the Genesee Valley.

CONTINUING STUDIES WILL ASSESS FUTURE IMPACTS

The long-term lowering of aquifer hydraulic heads creates the potential for permanent compaction of the aquifer system and additional land subsidence. The distribution of compressible sediments and their mechanical behavior need to be better understood in order to predict potential impacts. The sources of poor-quality water and potential paths of migration in the aquifers also need to be assessed in order to evaluate and predict changes in ground-water quality throughout the Genesee Valley.

The USGS is currently implementing conceptual and numerical models of ground-water flow in Genesee Valley to assist in determining the impact of mine flooding on the regional aquifer system. Drainage of ground water into the collapse areas is being simulated using data collected by ANSI consultants; the State Departments of Law, Environmental Conservation, and Health; Livingston County; local citizens; the USGS; and others. The models will provide insight into the problems of lowered ground-water levels, land subsidence caused by aquifer-system compaction, and migration of mineralized ground water.