LAND SUBSIDENCE

CASE STUDIES AND CURRENT RESEARCH

Proceedings of the
Dr. Joseph F. Poland
Symposium on Land Subsidence

Edited by James W. Borchers
U.S. Geological Survey

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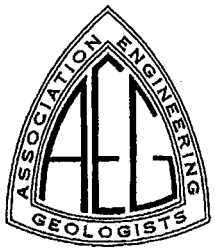

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Retsof Salt Mine Collapse and Aquifer Dewatering, Genesee Valley, Livingston County, New York

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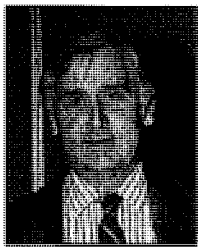

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ABSTRACT

Independent investigations by state and federal agencies have attributed the 1994 localized collapse and subsequent flooding at the Akzo Nobel Salt, Inc. (ANSI) salt mine near Cuylerville, New York, to collapse of bedrock and valley fill above an area of excessively wide yield-pillar panels. The 11.5-mi^2 room-and-pillar mine is located about 1100 ft beneath a glacially scoured valley. The mine filled with water in 21 months at a rate estimated to have been nearly 30,000,000 gal/day and drained ground water from overlying bedrock and glacial deposits. Surface subsidence is attributed to mine collapse, as well as to sediment compaction due to lowering of hydraulic head in unconsolidated valley-fill aquifers.

Horizontal stresses, well documented in western New York, may have been responsible for loading the rock overburden to critical stress levels prior to mining. Regionally occurring high horizontal stress, combined with additional stress concentrated by the topography of the buried valley, may have created a broad valley anticline and fractures that are inferred to coincide with the axis of the buried valley. The collapsed panels were developed beneath the area where rock quality is inferred to have been affected by preexisting stress. The resulting stressed rock appears to have been mechanically incapable of providing the structural integrity required for the successful application of the yield-pillar mining

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The authors gratefully acknowledge James T. Neal, Sandia National Laboratories; Peter W. Huntoon, University of Wyoming; and George A. Kiersch, Kiersch Associates, Inc., for reviewing and providing helpful comments on the draft of this manuscript. The authors take responsibility for any oversights and for their geologic interpretations of the data discussed.

Information relating to the Retsof mine was obtained from the document repository created as a condition of the New York State Attorney General's Office MOU at the State University of New York college library (Geneseo, New York) and from unpublished documents recently released by the NYSDEC following Freedom of Information Law Request.

method at the designed scale. This case history underscores the importance of geological and geomechanical exploration and characterization of rock and soil masses prior to engineering design.

INTRODUCTION

The Retsof mine (figs. 1–5), currently owned by Akzo Nobel Salt, Inc. (ANSI), was an 11.5-mi^2 room-and-pillar salt mine beneath the Genesee Valley that had operated since 1882. The salt horizon is between 900 and 1200 ft below the ground surface, depending upon the local topography and the regional southerly dip of the strata (~42 ft/mi; S5°E). Salt was mined until December 1995 from the Vernon Formation B-6 salt bed, which ranges from 18 to 26 ft thick throughout the mine area. The minable thickness of salt ranges from 9 to 16 ft, depending on the amount of shale interbedded near the upper and lower contacts of the salt bed (Denk and others, 1994). Most of the recent mining has been in the eastern half of the mine, which expanded downdip and eastward beneath the glacially scoured Genesee Valley.

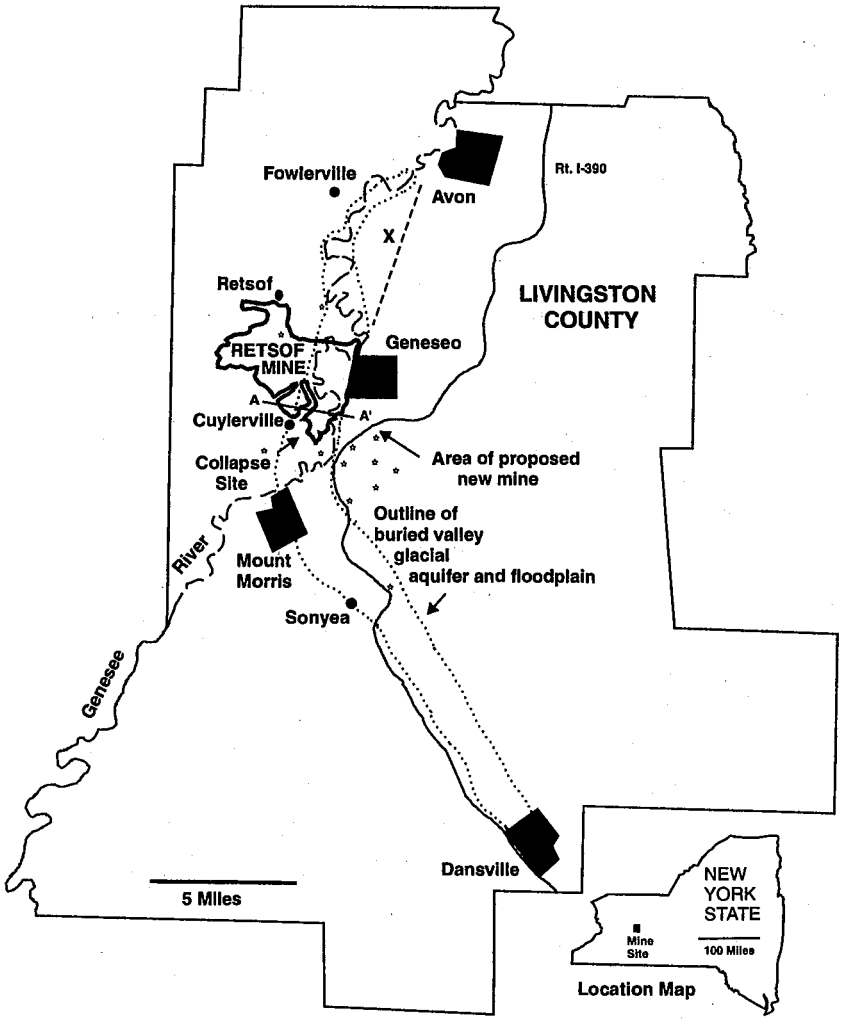

Figure 1. Location map for Akzo Nobel Salt, Inc. Retsof Salt Mine in Livingston County, New York. Cross section AA′ shown on figure 6. Large Wisconsin moraine complex (X) narrows the floodplain and displaces the modern Genesee River west of the older, buried glaciated valley (east valley margin shown by dashed line). Stars are approximate locations of borings used to infer valley anticline that are not shown on figure 2.

The Genesee Valley is filled with a southerly thickening (up to 700 ft), relatively unexplored sequence of glacial drift, which is capped by about 50 ft of postglacial fluvial sediments (figs. 3, 6, 7). The buried longitudinal profile of the valley follows the approximate dip slope of the resistant Onondaga Formation. The buried relief within the glaciated valley results in a thickening of the valley fill from about 300 ft near the northern edge of the mine to about 535 ft near the southern margin, a distance of 3 mi.

In March and April 1994, bedrock and valley

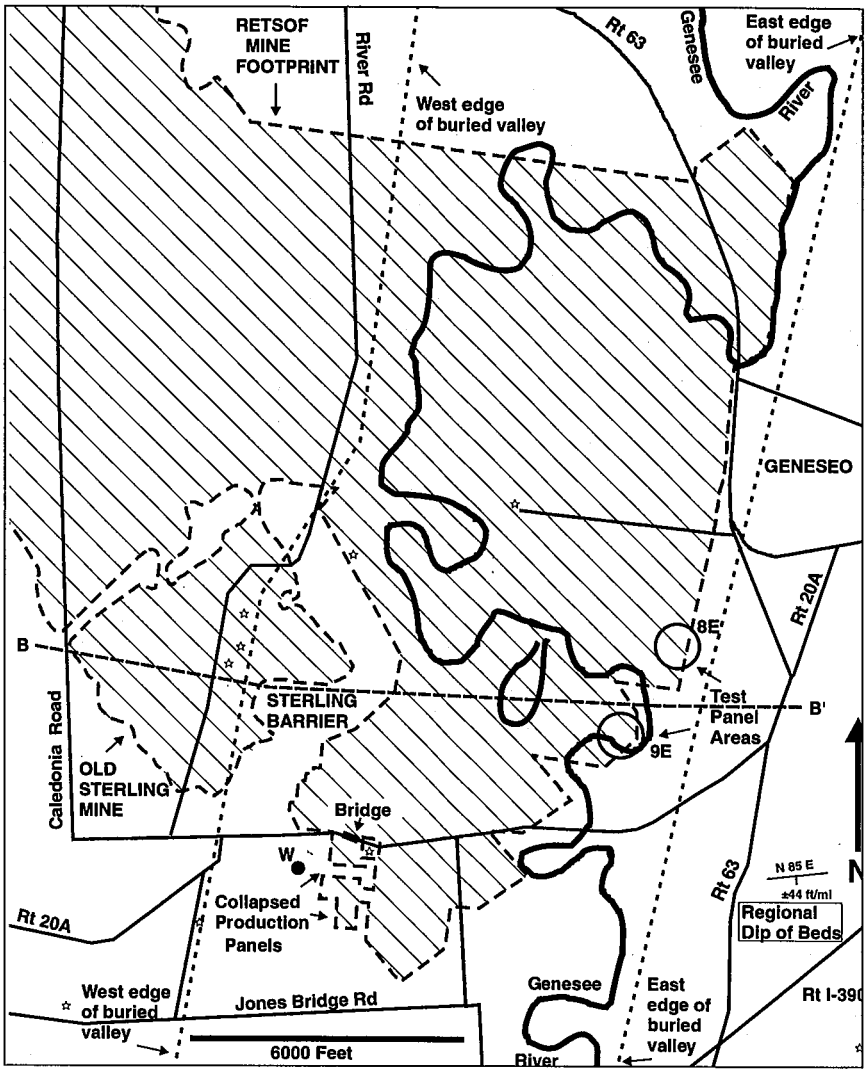

Figure 2. Enlarged view of southern portion of the mine showing the location of collapsed production panels and smaller test panels. W marks the location of the only stratigraphic test well in the map area that has a detailed log of glacial stratigraphy. Cross section BB′ is approximate location of figure 3. Profile K (fig. 9) parallels Jones Bridge Road at the base of the map. Stars are approximate locations of additional borings used to infer valley anticline.

fill overburden collapsed above two newly designed yield-pillar panels (Lundgren and Young, 1995). The collapsed panels (figs. 2–5) are near the thalweg of the buried valley, where the bedrock thickness between the mine roof and the base of the 535-ft-thick valley fill is about 600 ft. The collapses formed two contiguous depressions along a small floodplain tributary (Beards Creek) feeding the Genesee River. Ground water entered the mine

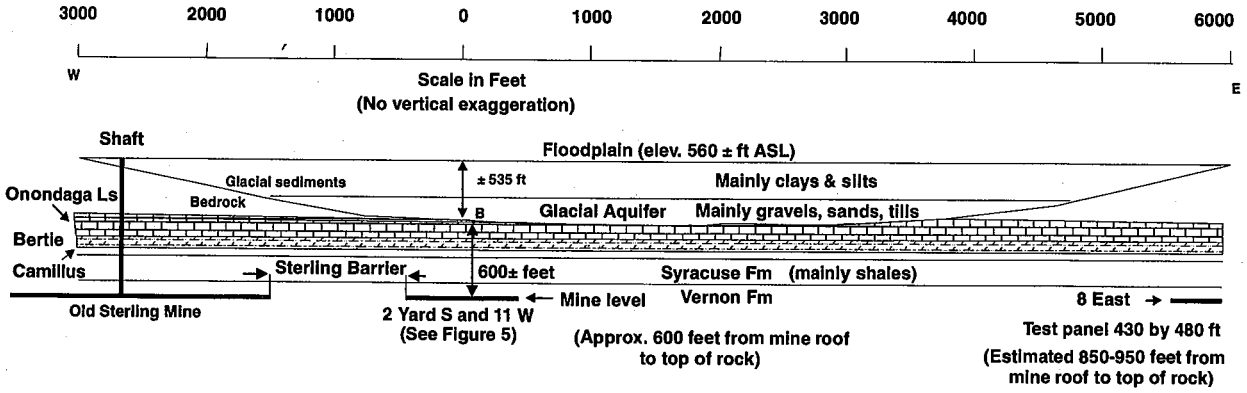

Figure 3. Approximate true-scale cross section of Genesee Valley depicting relationships of critical mine areas and significant aquifers. Dimensions of collapsed panels near center of valley can be seen on figure 5. Approximate location of section is shown on figure 2 at BB′. Vertical bedrock relief is approximately 900 ft (fig. 6).

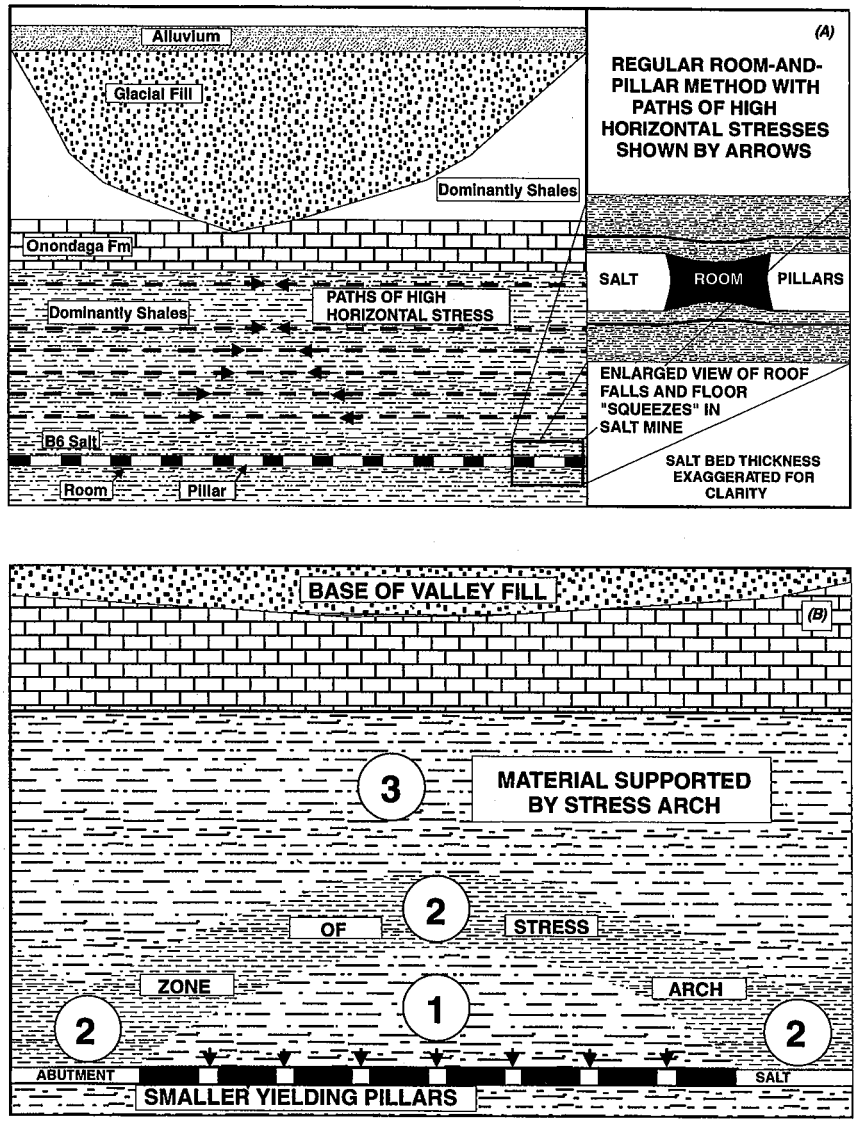

Figure 4. Diagrammatic cross sections showing conditions in typical room-and-pillar mines and reduction of problems with yield-pillar method (see fig. 6 for accurate scale).

(*A*) Normal pillars and roof and floor stability problems under conditions of high horizontal stress. Vertical exaggeration 10×.
(*B*) Schematic view of early stage of yield-pillar extraction with circled numbers indicating zones of
(1) unstressed rock; supported by yielding pillars,
(2) arcuate zone of high compressive stresses; arches develop higher compressive stresses due to the removal of underly ing support of zone 1, by yield-pillar deformation, and by accepting the gravity load (weight) of the material above
(3) materials supported mostly by stress arch of zone 2.

When the Retsof yield-pillar panels were enlarged to between 10 and 14 pillars (fig. 5), the stress arch lengthened and probably migrated toward the bedrock–valley fill interface.

from the Onondaga and Bertie formations and from the immediately overlying glacial aquifer, which is hydraulically connected to the fractured and weathered Onondaga Formation. Apparently, contribution of surface water to mine flooding was minimal due to the presence of a thick glaciolacustrine aquitard (figs. 3, 6, 7) at the top of the glacial sequence and directly below the thin alluvial cover.

Early attempts were made to pump the water out of the mine and to explore the feasibility of grouting the collapse zones. However, after a few months of subsurface investigations and rapidly increasing ground-water inflow, which stabilized at rates estimated between 18,000 and 22,000 gpm, attempts to prevent the mine from completely flooding were abandoned. While the mine was filling with water from the lowest elevations northward, mining continued along the northern (highest) perimeter of the salt bed.

The mine filled in approximately 21 months, March 1994 to January 1995. To a first approximation, this time interval is consistent with filling a 10.5- to 11-mi^2 mined-out area with an assumed 50–60 percent overall extraction ratio and average room height of 12–15 ft at the estimated inflow rate of approximately 30,000,000 gal/day.

MINING METHODS AND PRELIMINARY COLLAPSE INVESTIGATIONS

Room-and-Pillar Mining Method

The typical dimensions of the recent, large room-and-pillar mining pattern used under the valley consists of pillars measuring 80×75 ft (nominal "80-ft pillars") separated by 65-ft rooms (Denk and others, 1994). This scenario would produce a theoretical extraction ratio of 70 percent. However, due to irregular pillar design, actual pillar patterns measured on large-scale mine maps suggest that extraction ratios were between 50 and 60 percent in many areas.

Yield Pillar Technique

Stress control mining or the stress control method using yielding pillars is a controversial, relatively new technique designed to minimize the effects of roof and floor failure in underground mines. The technique is intended to form a protective stress arch or stress envelope (Dickie and Serata, 1993), which reduces the need for other support systems, such as roof bolts (fig. 4). Rooms are typically grouped together in panels and are separated by narrow yielding pillars (Dickie and Serata, 1993). The small pillars yield relatively quickly so that the individual stresses normally surrounding each pillar combine into a larger, broader "stress envelope" (or pressure arch) surrounding a panel, which is composed of yield pillars and intervening rooms (figs. 4, 5). The dimensions and design of the entire panel, as well as

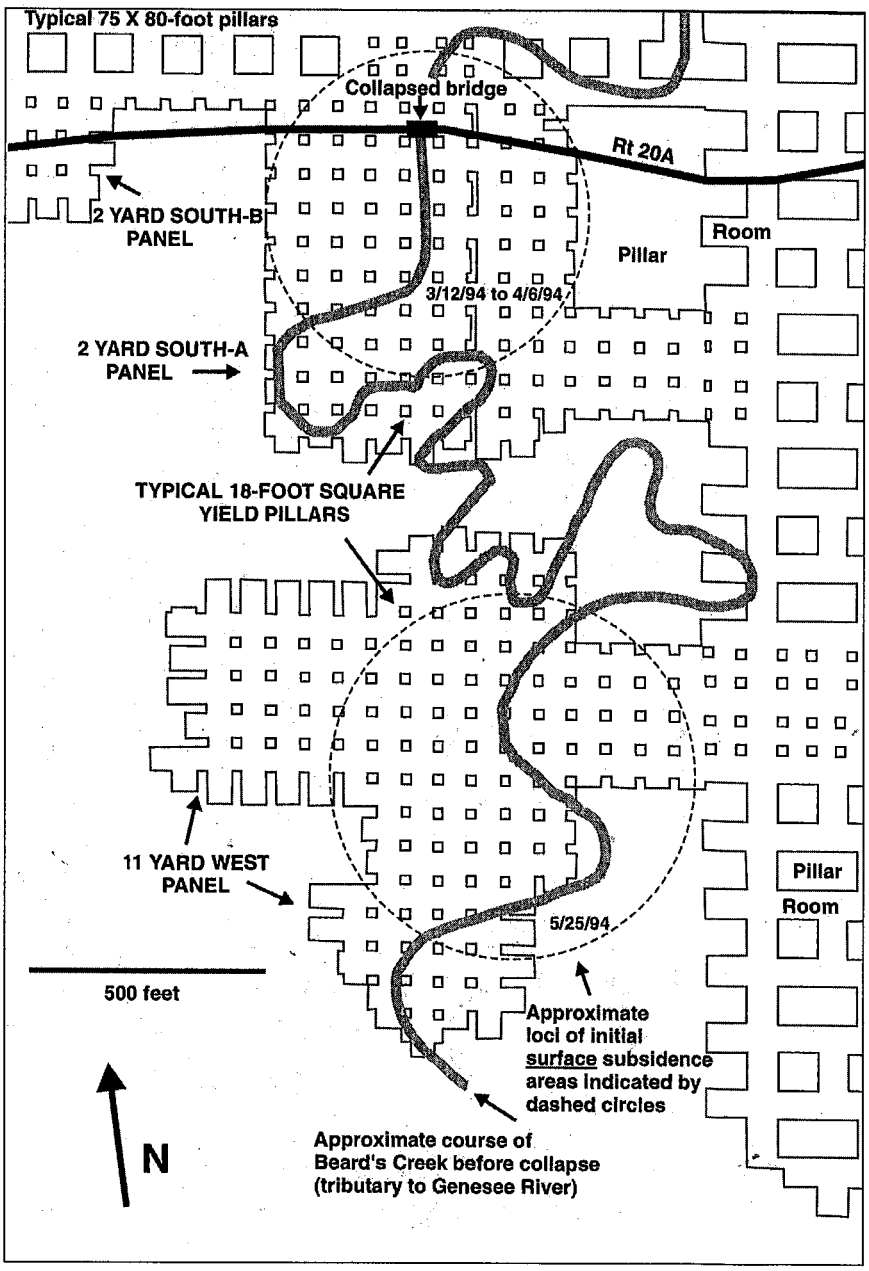

Figure 5. Enlarged view of collapsed yield-pillar panels showing panel areas, relative pillar sizes, and surface geographic features impacted by collapse. Terminology follows that of Denk and others (1994). Panel areas directly traced from 1:2400 scale 1994 map by Akzo Salt, Inc. Original roof collapse at mine level occurred March 12, 1994. Dates indicate development of early significant collapse depressions at the ground surface. Dashed circles show approximate extent of major surface depressions and circular fracture development as of 1994.

the particular geology of the overlying bedrock overburden, determine how high above the mine roof the broadened stress envelope will concentrate the combined stress, which is transferred either to the adjacent, unmined beds or to suitably designed larger abutment pillars. The successful yielding anticipated for the smaller pillars is signaled by the eventual decrease in floor-to-roof convergence rates as load is shifted from the yield pillars to the abutment pillars. In theory, the newly formed arch or stress envelope above the panel distributes the load to the sides of the panel, whereas the small yield pillars are left supporting only the load remaining between the immediate mine roof and the base of the pressure arch (fig. 4). As panel dimensions increase, the location of stress concentrations above the mine roof can be determined by strain gages inserted into holes bored into the overlying strata (Serata, 1975).

Depicting a mine similar to the Retsof mine, figure 4 schematically shows the manner in which the yield pillar method reduces mine roof and floor problems caused by high horizontal stresses, which are the result of regional stresses, topographic effects, likely mine-induced stresses, and the yield pillar mining plan. As shown in figure 4, yielding pillars create a sagging of the panel roof that redistributes the horizontal stresses in the immediate roof to the pressure arch above.

As traditional room-and-pillar mining progressed under the Genesee Valley, problems with roof falls and floor heaves increased (Denk and others, 1994). A yield-pillar design was implemented near the central portion of the valley following construction of the two smaller test areas located near the eastern margin of the bedrock valley (fig. 3). The first test panel (430 × 480 ft) was constructed by splitting preexisting large pillars into four smaller pillars, each 20 × 25 ft, and with an overall extraction ratio of 90 percent. The second test area involved the splitting of an additional 13 large pillars into 20-ft^2 sections with an overall 350-ft span width and a 92 percent extraction ratio (Denk and others, 1994). Available data suggest that the bedrock thickness above the test panels may be nearly 50 percent greater than above the collapsed panels, due to the shallowing of the bedrock cross section profile caused by the glacial scouring of the valley (fig. 6).

Collapsed Panels

The two yield-pillar panels that collapsed near the center of the valley (fig. 5) consisted of 20 × 20 ft pillars separated by 54-ft rooms. The approximate dimensions for the two collapsed panels, as traced from ANSI maps for 2 Yard South-A and 11 Yard West, are shown on figure 5. The pillar dimensions at the first production panel (2 Yard South-A, begun January 1993) were later decreased from 20 ft to 18 ft to control apparent "floor heave" (Denk and others, 1994). This resulted in an extraction ratio of 92 percent. Laser surveying later revealed that the increase in the floor-to-ceiling convergence rate, which occurred after the first production panel had been widened to 550 ft over a period of 7 months, was actually about 80 percent roof movement (Denk and others, 1994).

This first panel (2 Yard South-A) was abandoned in November 1993, after "10 crosscuts of advance (approximately 760 ft)" due to "deteriorating ground conditions, increased closure rates, and production difficulties" (Denk and others, 1994). This followed 25 in of total convergence at a rate that had accelerated to 15 times that measured in the pilot test areas and about 10 times that seen in the standard room-and-pillar areas. Prior to ultimate collapse, the convergence rate accelerated further, leaving only about 3 ft of clearance and tension cracks in the roof (Denk and others, 1994).

Mining began in the second panel (11 Yard West) that collapsed in March 1993 with 18-ft pillars, 54-ft rooms, and a 90 percent extraction ratio. This panel was driven 10 rooms wide, and was anticipated to connect with 2 Yard South-A (fig. 5). However, the second panel showed high convergence rates after 500 ft of advance and was abandoned in February 1994; over 20 in of total convergence were measured with severe pillar spalling (Denk and others, 1994). A roof frac-

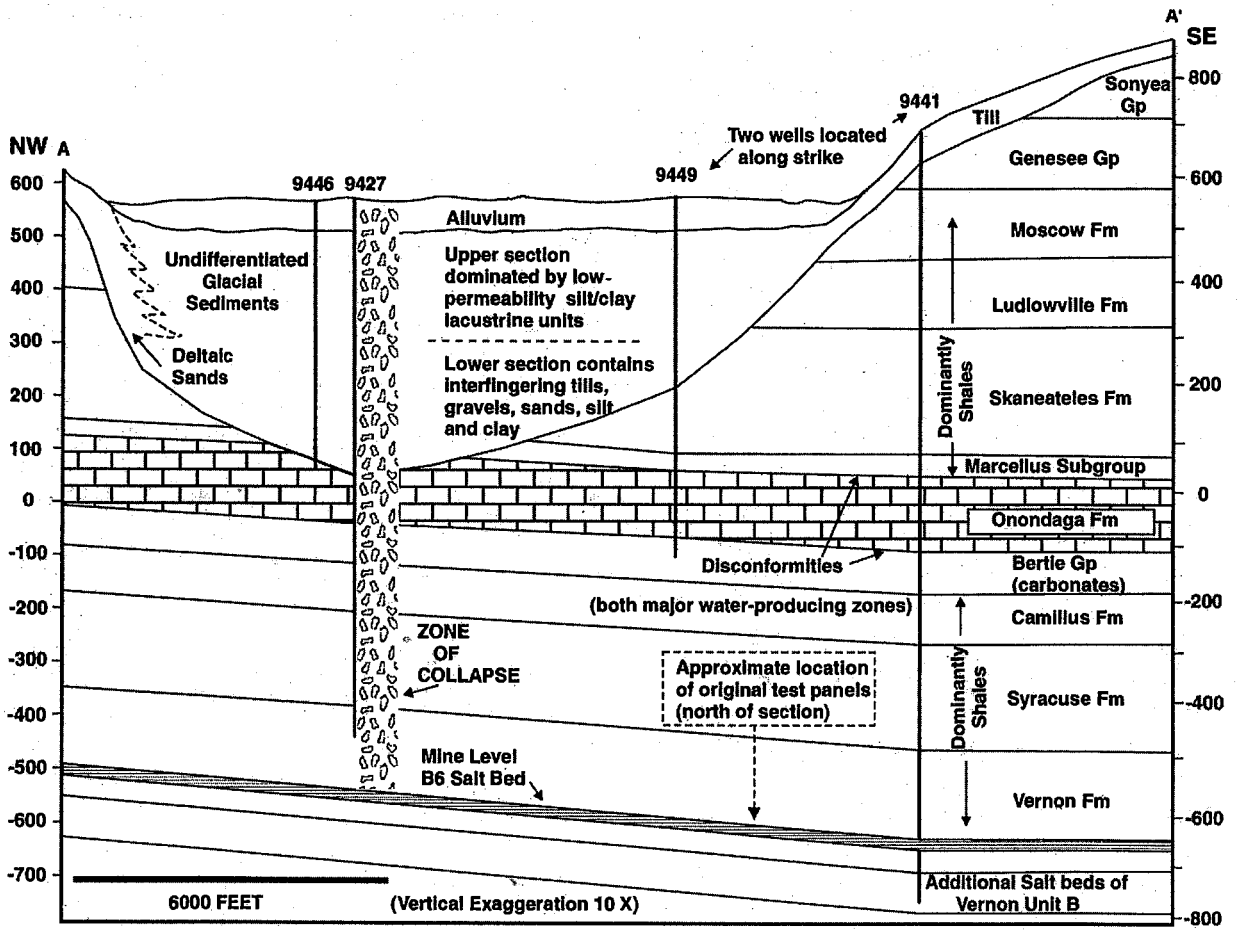

Figure 6. Schematic cross section of Genesee Valley based on figures in GZA Environmental (1995). Thicknesses of units are approximate on cross section and inferred geologic relations between boring locations are based on additional limited data close to the section shown. Onondaga-Bertie contact in well 9449 is 10 ft higher than same horizon in 9441, although both borings are located along regional strike. Differences in contact elevations may be accounted for by gentle upwarp of strata toward the valley center. Some other borings used to detect subtle upwarping of strata along the valley axis are shown on figures 1 and 2 (stars). Approximate location of section is on figure 1 at AA'.

ture had also developed that encircled much of the perimeter of 11 Yard West. A few other small yield pillar areas were excavated at about this time in the southern end of the mine, but they were not enlarged to the dimensions of the two collapsed panels.

Conclusions of Collapse Investigations

U.S. Mine Safety and Health Administration

A U.S. Mine Safety and Health Administration (MSHA) investigative team (Denk and others, 1994) concluded that the panel collapses were "primarily the result of two interrelated factors: (1) abnormal geological conditions in and around the panels; and (2) inability of the overburden to adequately bridge the larger spans created above 2 Yard South-A and 11 Yard West by the yield-pillar panel configurations." The MSHA report also states, "Prior to the implementation of the yield-pillar mining method, exploratory drilling in this area may have provided information that could have influenced the design of the panels and mining in this area."

John T. Boyd Report

An independent impact analysis by the John T. Boyd Company (1995) for the New York State Department of Environmental Conservation (NYSDEC) includes the following analysis. "The principal cause of the mine collapse is the use of yield pillars in an area where solid rock cover is insufficiently thick to accommodate the formation of a wide arch.

As the pillars yield by design, the overlying strata must form a rock arch to span the panel and carry the load to less yielding mine elements at the panel edge, such as unmined salt blocks or barrier pillars. Increasing panel widths require a corresponding increase in rock arch thickness and width. For the yielding pillars in the 2 Yard South and 11 Yard West panels, the rock arch that formed in the overburden was too wide for the applied load and collapsed."

The following observations also are contained in the Boyd Report: "Before committing to a production panel that is wider than the test panel, it is appropriate to examine the arch that will form in the overburden to access its stability." (John T. Boyd Co., 1995, p. 4–9). "The apparent deficiency in this otherwise acceptable new pillar design procedure is [sic] the closure data were either not interpreted by Akzo or they failed to react to the interpretation." (John T. Boyd Co., 1995, p. 4–11).

Rock Mechanics Report by International Mining Services, Inc.

Akzo Nobel consultant's analysis of the collapse by International Mining Services, Inc. cites the following evidence that the ground conditions in and around the production panels were in some way anomalous: (1) ground penetrating radar results; (2) increased down warping of rock into salt pillars; (3) the occurrence of limited gas and water volumes in mining sections; (4) the increasing occurrence of local roof falls ; (5) increasingly higher closure rates in mining rooms; and (6) high closure rates from the start of mining in both of the yield-pillar production panels (International Mining Services, Inc., 1994). Items 1–4 refer to conditions encountered outside the yield pillar panels.

Rock Mechanics Assist

Gary Peterson of Rock Mechanics Assist (Dryden, New York) provided written comments to Akzo Salt (prior to their name change to ANSI) on the excessive closure of the 2 Yard South-A panel shortly after it was abandoned in October 1993 (Peterson, 1993). Peterson's assessment (written nearly 4 months prior to the first collapse) includes this comment: "At first glance it appears that the experiment was too wide thus exceeding the critical width." His "preliminary assessment" also states that the panel was, "in an area which was preloaded by mining 1 Yard South and 2 Yard South." He further states, "It also appears that the east abutment was made too small when mining the 3 entries from 1 Yard South at room 61." The locations of 1 Yard South and 2 Yard South referred to by Peterson are immediately east and north, respectively, of the collapsed panel at 2 Yard South-A (fig. 5).

QUALITY, TRENDS, AND AVAILABILITY OF DATA

A lack of quantitative subsurface geotechnical information throughout much of the area impacted by the mine collapse and by the dewatering of the valley aquifer system severely limits geologic and hydrogeologic analyses (Nittany Geosciences, Inc., 1995). Comprehensive, randomly located data sets were not compiled immediately after the collapse. ANSI periodically has expanded a network of monthly subsidence elevation surveys, the majority of which tend to follow accessible highway or railroad rights-of-way. However, there was a tendency to initially disregard subtle impacts on private wells several miles from the collapse until a more widespread pattern of subsidence and

ground-water changes became obvious. This pattern was manifested as low water levels, dry wells, increased turbidity, natural gas emissions, and increased hardness and salinity throughout the deeper glacial aquifer.

Very little geotechnical drilling data were available prior to June 1995. One of the best potential sources of glacial aquifer data was more than 30 borings completed to explore grouting options around the collapse areas. However, these were not logged in detail through the 500 ft+ valley-fill glacial sequence. This appears to have resulted, in part, from the assumption that the major source of ground water entering the mine was the bedrock interval in the Bertie and Onondaga formations, rather than the glacial aquifer immediately above and hydraulically connected to these relatively low-yield carbonate rocks.

Drill logs of five test wells, recently completed for a U.S. Geological Survey aquifer study, fully penetrate and partially characterize the glacial valley-fill aquifer system that extends more than 15 mi along the valley (fig. 1). Three of these wells are within 7000 ft of the collapse; with the other two located approximately 7 mi south and 8 mi north of the collapse (fig. 1).

Water-level measurements in many wells completed in the deeper, coarser grained portion of the glacial aquifer (fig. 6) showed that hydraulic head continuously declined through May 1996 regardless of seasonal fluctuations in shallow wells (Akzo Nobel Salt, Inc., 1994–1996). Water levels in several deep glacial aquifer wells located in the 8-mi valley segment north of the collapse site declined an average of about 6 in/week through January 1996. One 329-ft valley-fill water well, located 3.2 mi south of the collapse, experienced a water-level decline of 150 ft between March and October of 1994 (~4.8 ft/week). Several water wells to the south in the valley went dry and vented significant amounts of natural gas.

As of June 1996, water levels in a few deep observation wells near the collapse were rising, but water levels in many deep valley aquifer wells a few miles away had merely slowed their rate of decline or showed little or no recovery, regardless of above-normal spring rainfall. Localized recovery of water levels in observation wells at or near the collapse site may be artificially enhanced by surface water flowing into damaged wells in the collapse area. At least two exploratory wells sank beneath land surface or suffered casing failures early during discrete episodes of collapse, and could provide conduits from Beards Creek to deep aquifer zones.

GROUND WATER AND GEOLOGIC ISSUES

Issues that are most relevant to the past and future subsidence phenomena in the Genesee Valley are closely related to the changing rates of closure of the mine cavity and the inseparable settlement effects attributable to aquifer dewatering. Data collected outside of the mine boundary could help to distinguish among these impacts. The asymmetric, north-south dewatering of the valley aquifer resulting from the mine flooding has been one of the most widespread impacts to date (Akzo Nobel Salt, Inc., 1996a). Analysis of the aquifer and its behavior during dewatering and recharge can provide important data for distinguishing between mine subsidence and settlement related to aquifer dewatering.

Important additional stratigraphic logs, geotechnical data, and relevant in-situ bedrock stress measurements at the valley edges immediately east of the Retsof Mine from the proposed Hampton Corners mine and for the former Sterling Mine area west of the main Retsof Mine (fig. 2) were recently obtained following public hearings (Akzo Nobel Salt, Inc., 1995). This information, combined with the five logs from the ongoing study by the U.S. Geological Survey and existing data and references, indicates that ground water and geologic issues relevant to an understanding of the mine collapse and interrelated subsidence impacts are as follows.

Glacial Sequence

The glacial sequence in the mid-valley area is capped by a thick section of relatively impermeable glaciolacustrine clays and silts deposited during ice withdrawal from the valley (figs. 6, 7). Marginal proglacial lake deltas existed along the valley sides when proglacial lakes occupied the valley. These deltaic sands and gravels probably provide pathways for recharge of ground water from the valley margins to glacial sediments deeper in the buried valley (Muller and others, 1988). This assumption is supported by rapid water-level declines (less than 10 days after the first panel failed) in several shallow valley-margin wells over a mile southwest of the collapse. Studies in similar Finger Lakes valleys also indicate that glacier recession in large, north-south valleys produced buried, esker-like bodies or layers of coarse permeable sediments in the lower portions of buried bedrock valleys that resulted from strong subglacial meltwater discharges into deep proglacial lakes (Mullins and others, 1991). Such coarse sediments are probably discontinuous in the Genesee Valley due to the

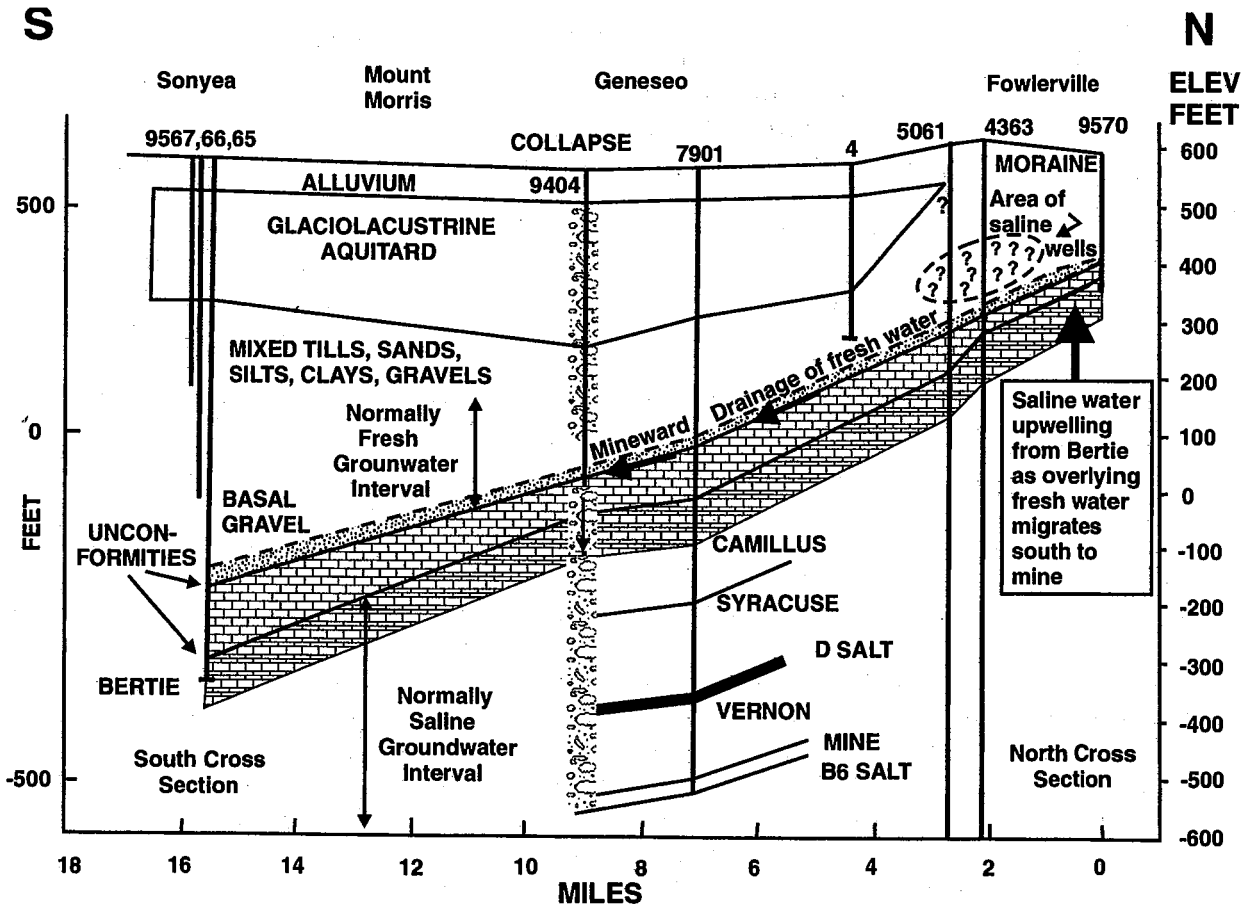

Figure 7. Longitudinal profile along approximate base (thalweg) of buried bedrock valley beneath floodplain based on existing oil and gas wells and postcollapse drilling logs. Geology diagrammatic and scales are approximate. Section also illustrates upwelling of saline ground water from Bertie Group and older rocks where Onondaga cap thins. Southward migration of saline ground water follows regional dip and basal glacial aquifer toward collapse. Vertical gradient driving saline water upward probably reflects upland ground-water recharge, typical of such valleys. Some wells that penetrated a glaciolacustrine aquitard near the valley center flowed prior to mine collapse.

erratic nature of ice recession and obvious moraines that cross the valley.

Ground Water

Shallow ground water outside the floodplain margins generally is confined to till or to fractures and bedding-plane partings in shale, which are recharged through the heterogeneous cover of glacial drift (Cadwell, 1988). Deeper ground water is concentrated within fractures, bedding features, and solution zones in the top of the weathered Onondaga Formation, which subcrops along the valley axis. The disconformable contact between the Onondaga and underlying Bertie Group is also a water-bearing horizon, and apparently marks a downward transition from fresher to more saline ground water, reflecting the evaporite beds in the underlying Salina Group rocks (figs. 6, 7).

Bedrock wells tapping the most productive carbonate units and unconformities seldom produce more than several tens of gallons per minute. The fractured shales have much lower yields. Ground water production from shallow fractured bedrock aquifers outside the valley proper generally is low. Existing water wells within the valley generally are shallow because adequate water is normally encountered in the shallow fluvial sediments or at moderate depths in some shallow glacial deposits (moraines). The glacial aquifer in the Genesee Valley directly overlies the fractured, eroded top of the Onondaga Formation from just south of the mine northward for over 9 mi. The connected glacial and bedrock units comprise a complex, interconnected aquifer system.

There is a lack of detailed information on potentially permeable geologic structures, such as small faults, due to the poor quality of existing water-well logs and the limited geologic database in such a rural region. However, many small high-angle faults encountered in engineering projects in adjacent Monroe County suggest that unrecognized faults with small displacements may be relatively common in the Devonian section of central New York. Such faults are invariably important ground-water conduits as encountered in local engineering projects by R. A. Young. Evidence of high-angle faulting on the east flank of the valley is postulated from low-resolution seismic data collected for the new mine (Alpha Geoscience, 1995).

Prior Ground-Water Inflow to the Mine

Little or no ground water previously reached the level of the flooded mine, except through leaks along old vertical access shafts. This lack of water entry indicates that fracture permeability extending to the mined horizon was probably minimal prior to mining-induced fracturing. Engineering documents from the old Sterling Mine indicate that gradual mine closure and salt solution increased bedding separations in the rock overburden and enhanced ground-water connections between the glacial aquifer and bedrock at the valley margins (Langill, 1987).

Regional Decollement

Regional decollement thrusts and compressional deformation structures of limited displacement have been encountered in central New York salt mines 50 mi to the east near Cayuga Lake (Prucha, 1968). A few small thrust-like structures are described in the Retsof mine (Dunn Corporation, 1992), but any larger, undetected, regional Paleozoic compressional structures, if they are present, are probably in the deeper Vernon salt beds below the Retsof (B6) horizon.

Ground-Water Changes as Evidence of Dewatering Mechanisms and Magnitude

Water-quality measurements in private wells north of the mine (D. Napier, New York State Health Dept., 1996, oral communication) showed that water of increased salinity is moving southward toward the collapsed area. These measurements indicate that increasingly saline ground water from evaporite beds higher in the stratigraphic section above the mine is

moving south (downdip) toward the mine collapse within the lower valley fill aquifer (fig. 7). This saline interface presumably is not related to the B-6 salt bed or the dense brine in the flooded mine. Thin evaporite beds are scattered through rocks from the Bertie Group downward.

The southward migration of saline ground water probably results when brines in the bedrock rise in response to the reduction of hydraulic head in the deep glacial aquifer caused by dewatering associated with the mine collapse. Theoretically, a small reduction of hydraulic head in a fresh, water-table aquifer would cause a much greater upward migration of denser brackish water below (Freeze and Cherry, 1979). Presumably, after the brines enter the basal glacial aquifer they move toward the mine collapse area in response to hydraulic gradients in the basal glacial aquifer (fig. 7). Hydraulic gradients in the bedrock underlying the center of the Genesee Valley probably are driven by higher hydraulic head in upland recharge areas as is common in most large valleys.

Subsidence Due to Sediment Compaction

The reduction of hydraulic head in the deep glacial aquifer is reflected in subsidence contours that are elongated parallel to the valley axis for at least 7 mi (Akzo Nobel Salt, Inc., 1996a, b). At a given distance from the collapse zone, wells in the lower aquifer drilled in the axial part of the valley have lower hydraulic head than wells drilled close to the valley margins (Nieto, 1995) (fig. 8). However, water levels in wells located between 7 and 9 mi from the collapse dropped further than water levels in some valley margin wells that are closer to the collapse zone. Subsidence profile line K, which is located about 2000 ft south of the mine boundary and parallel to Jones Bridge Road (fig. 2, bottom), suggests that an axial zone of higher permeability occurs beyond the zone of influence of mine subsidence (fig. 9).

Subsidence shown in the profile most likely results from compaction of glacial sediments due to an increase in effective stress caused by a reduction of hydraulic head as the aquifer

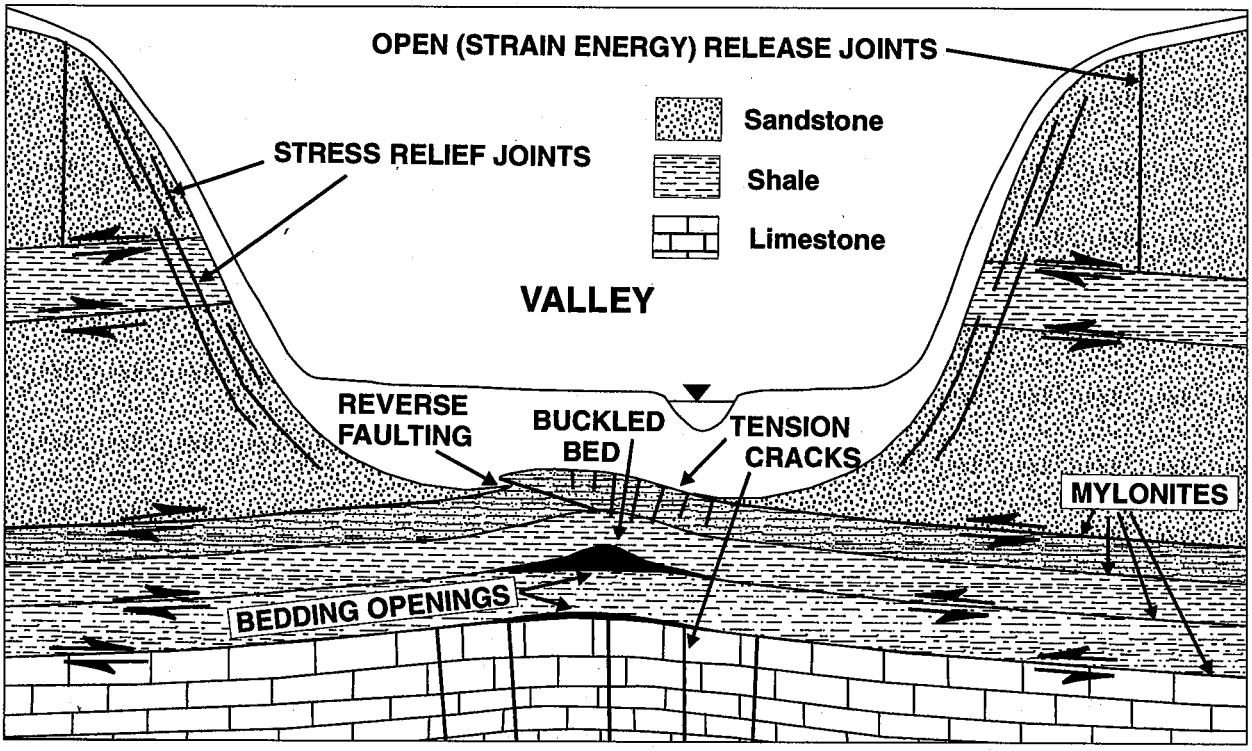

Figure 8. Valley-related features associated with horizontal stresses and erosional topography developed in sedimentary strata. This figure is diagrammatic and not to scale; redrawn from Nieto (1977), as published in Fisher and Banks (1978), and in Kiersch (1991).

was dewatered. Aquifer compaction in response to ground-water withdrawal is described by Riley (1997, this volume). Subsidence of similar character occurs in many of the ANSI profiles. Because the thickness of the aquifer is fairly uniform under the area of the subsidence profile (figs. 3, 6) differences in aquifer thickness probably do not explain the differences in subsidence between stations on each profile (fig. 9). The convergence of the convex-upward eastern and western limbs of each profile near the middle of the valley (near K10) suggests the presence of a narrow axial ground-water sink (narrow zone of maximum depressurization and compaction) and therefore, an underlying zone of enhanced permeability that allows ground water to flow toward the collapse. If the thickness of the aquifer were the sole factor controlling the amount of compaction and subsidence, such east-west subsidence profiles should have a more gradual, trough-shaped bottom (Nieto, 1995).

Water from the deep glacial aquifer probably flows toward the valley axis and downward to the fractured Onondaga Formation. Then, this water is rapidly transmitted for long distances (north and south) along the valley axis toward the collapse zone. Gravels at the base of the glacial aquifer are assumed to be present in the section shown (figs. 7, 9) and to contribute to the transmission of water from the glacial aquifer to the collapse area or an axial fracture zone in the bedrock.

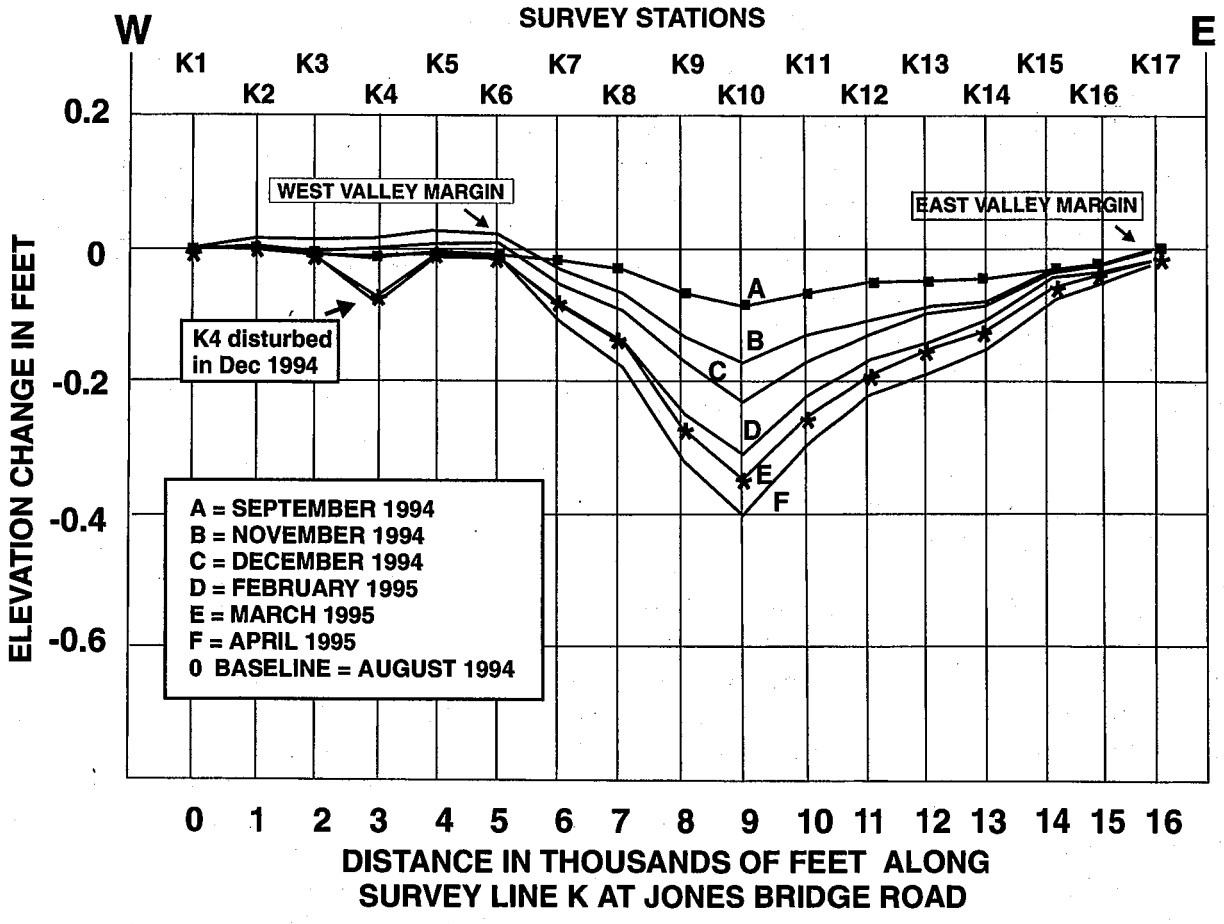

Figure 9. Subsidence along survey line "K" at Jones Bridge Road (fig. 2), south of mine boundary and mine collapse. Significance of doubly convex-upward shape of subsidence profiles is discussed in text. This figure was replotted from survey data in Akzo Nobel Salt, Inc.(1996b); actual data points for some plots were omitted for clarity. If the point of maximum subsidence in valley actually lies between K9 and K10, convex-upward shapes of curves could actually be greater than shown.

However, the deep glacial aquifer is nonuniform and contains anastomosing sands, gravels, and tills, as demonstrated by the diverse pressure heads in the five recently completed test well clusters (Alpha Geoscience, 1995). Much more information is required before the ground-water flow system is understood completely.

STRESS CONDITIONS UNDER VALLEYS

Valley Anticlines

The geotechnical literature contains numerous references and studies describing the existence of low-amplitude anticlinal "upwarps" beneath sedimentary valleys (Ferguson, 1967; Matheson and Thomson, 1973; Nieto, 1977). These structures are called valley anticlines or river anticlines and are described by investigators in the western United States (Huntoon and Elston, 1979; Sturgul and Grinshpan, 1975). Nieto (1977) extended the work of Ferguson (1967) and of Matheson and Thomson (1973) and concluded that the valley erosion process, irrespective of the intensity of horizontal stress, should lead to the development of up warping, buckling, separation of sedimentary layers, reverse and thrust faulting, and tension fractures (the latter developing in the "upper fiber" of gentle anticlinal folds). Figure 8, redrawn from Nieto (1977), was reviewed by Fisher and Banks (1978) and by Kiersch (1991) in the context of exploration and characterization strategies for the principal structures to be anticipated in regions of valley incision. The presence of high horizontal stresses would enhance the development of these features. Several other references summarize the occurrence of such deformational structures in mines located beneath valleys in the eastern United States (Overby and others, 1973; Molinda and others, 1992; Savage and Swolfs, 1986). Clearly, upwarping and fracturing parallel to valley axes can develop preferential fracture permeability in bedrock beneath the central portions of valleys, such as that described by Wyrick and Borchers (1981).

A wealth of stress measurement data in the eastern United States indicates that horizontal stresses are often larger than vertical stresses to depths of 3000 ft (Zoback, 1980). At depths of less than 1000 ft the ratio of horizontal to vertical stresses is commonly found to be between 2 and 4 (Nieto, 1977, 1995).

Valley Dimensions

Molinda and others (1992) studied failures of mine roofs under valleys and found that unstable roof conditions due to valley-related horizontal stresses were more common beneath broad valleys than under narrow valleys. They measured the distributions of 169 unstable mine roofs with respect to valley shape, where valley shape was defined as the confinement factor measured as R/W (R = valley relief, W = width of valley bedrock floor). They found that unstable mine roofs were most common where the R/W ratio was between 0.2 and 0.6. The R/W confinement factor for the Genesee Valley above the mine is between 0.2 and 0.3, depending upon how valley floor width is measured. A reasonable assumption for the R/W ratio in the Genesee Valley near the south end of the mine is 900 ft/3500 ft or 0.26 (fig. 3).

Horizontal Stresses at the Retsof Site

Evidence of bedrock valley axial deformation and accompanying high permeability along axial fracture zones in the Genesee Valley is discussed by Nieto (1995). The existence of higher-than-expected horizontal stresses has been confirmed by measurements for the proposed ANSI Hampton Corners mine along the eastern valley margin, where horizontal to vertical stress ratios are greater than two in the Onondaga Formation at a depth of 672 ft (GZA Environmental, 1995). As noted by other workers (such as Molinda and others, 1992), these values are typically higher in the axial portions of bedrock valleys.

Additional information supporting the existence of excess lateral forces on the west margin of the Retsof mine is contained in a 1979 field inspection report on the old Sterling Mine (Behre Dolbear and Co., Inc., 1979).

Appendix A of their report describes how the approach to "C" shaft is supported by "ring sets of yieldable arches" installed 10 to 12 years earlier. The authors state that, "During the time of the visit, one of the arches was showing signs of severe side forces which had caused it to deform close to the crown. The overall impression gained by looking at the ring sets is that they are oval-shaped with the long dimension vertical. This gives the impression that the main forces acting are side forces, but on the other hand, this may be the way the rings were set up. But whatever the forces, they are still active and the rings continue to yield and close up" (Behre Dolbear and Company, 1979).

Evidence for a broad anticlinal upwarp under the Genesee Valley can be deduced from close examination of boring logs scattered throughout the area, including the proposed location for the new ANSI mine (figs. 1, 2). In two test borings within a mile of where the high horizontal stresses at depth were measured, the elevation of the basal contact of the Onondaga Formation in wells rises 10 ft (11 ft/mi) along strike as the contact crosses into the valley from the east (Alpha Geoscience, 1995). At least four other well pairs (figs. 1, 2) that straddle the east or west valley margins exhibit 10- to 20-ft elevation anomalies with respect to the regional dip of the rocks measured at the base of the Onondaga Formation. In all cases the basal Onondaga/Bertie contact for wells in the valley is higher than the elevations of the same stratigraphic horizon on the valley sides. Stratigraphic contacts were projected onto a datum representing the regional dip of the strata (42 ft/mi) to locate elevation anomalies.

Data needed to accurately define the precise shape of the buried Genesee Valley are limited, but existing well data show that the valley is asymmetric in its east-west profile (fig. 6), and that the deepest point is closer to the western valley margin where the depression and subsidence effects have been greater. Within the limits of the available data, the two collapsed panels appear to coincide with the thalweg of the bedrock valley. The locations of precollapse roof falls on maps of the large pillar areas of the mine also conform approximately to the apparent valley thalweg trend (Nieto, 1995).

CONCLUSIONS

The majority of postcollapse studies have concluded that overburden rock above the yield-pillar panels did not have the shear strength and stiffness required to support the pressure arch developed by the mining method. Whether the initial convergence rate signaled the immanence of the collapse at a given time during the mining operation falls within engineering judgment, and that issue has not been addressed. The original test panels near the valley margin were developed where the proportion of rock in the overburden was significantly greater than over the collapsed panels. Furthermore it appears that (1) the horizontal stress at the collapsed panels should be higher than at the test panels and/or (2) that the overburden rock high above the collapsed panels might have been predisposed to failure because of defects caused by high horizontal stresses influenced by valley topography. Either the documented horizontal stresses or the inferred axial fractures (or both) may have contributed to a decrease in the ability of the overburden to support the pressure arch in the axial part of the valley.

A crucial question to be answered in the search for lessons to be learned from this mine collapse and ensuing environmental impacts is whether the unfavorable material properties of the overburden and the existing stress regime near the collapse could have been anticipated. Ample evidence appears to indicate that the geologic factors contributing in the collapse—a main roof of inadequate rock-mass quality—might have been anticipated by exploration and characterization programs conducted ahead of mining. Given the benefit of hindsight and examples in the existing geotechnical literature, a judicious exploration and characterization program for the geomechanics of the overburden and valley stress

conditions probably would have helped to answer this question. Even if the question is left unanswered, it would be highly imprudent not to evaluate such conditions in future mining operations.

POSTLOGUE: OFFICIAL AND COMMUNITY RESPONSE TO MINE-RELATED ISSUES

Memorandum of Understanding

The New York State Attorney General's Office coordinated the development of a Memorandum of Understanding (MOU) with the participation of Akzo Nobel Salt, Inc., the New York State Department of Environmental Conservation (NYSDEC), and the Livingston County Board of Supervisors. The MOU was intended to provide a formal agreement for development of (1) a Water Supply Contingency Plan (to deal with aquifer dewatering and impacts on private water supplies over an area extending some 15 mi or more along the valley axis), (2) a Property Damage/Mortgage Guarantee Plan, (3) a Subsidence Monitoring Plan (for both mine subsidence and aquifer dewatering), (4) Mine Collapse, Flooding, and Ground Support Reports, and (5) a Community Awareness Program (CAP).

Technical Assistance Group Committee

The CAP included the formation of a citizen's Technical Assistance Group Committee (TAG Committee), funded for 2 years with $50,000 provided by ANSI. The TAG Committee chose Shannon and Wilson, Inc. to provide independent geotechnical reviews and analyses of reports and data submitted by other consultants and ANSI. A preliminary community report by Shannon and Wilson, Inc. was completed in the spring of 1995, prior to public release of the majority of other independent engineering studies (Shannon and Wilson, 1995).

After the 1994 mine collapse, ANSI began permit applications with NYSDEC for a new mine at Hampton Corners immediately southeast of the flooding Retsof mine. The Environmental Impact Studies, Public Hearings, and Issues Conferences for the controversial new mine have provided some additional geologic data that are relevant to an understanding of the geologic setting of the Retsof Mine.

Status of Ongoing Independent Reviews

Community controversies relating to the impacts of the Retsof mine collapse and the new Hampton Corners mine proposal have not been completely resolved. Settlement of all existing damage claims and ongoing challenges to the NYSDEC permit for the new mine require a more comprehensive understanding of unresolved geotechnical issues.

This paper is an attempt to provide such an improved overview of critical geologic information. The analysis has benefited from additional limited geotechnical data developed for the Hampton Corners Mine and from data collected after the reports in the reference list were submitted, especially aquifer test studies. A. S. Nieto was retained by Shannon and Wilson, Inc. to evaluate the accounts of failure mechanisms proposed by other consultants and to comment on relevant geomechanical aspects of the problems that might require further study. R. A. Young (a member of the TAG Committee) has mapped and studied the geology and ground water of the area since 1966 as a faculty member of the State University of New York, as well as for the New York State Geological Survey and the U.S. Geological Survey (Muller and others, 1988; Mansue and others, 1991).

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