White Paper

Saline Tully Valley Mudboils
Origin and Mitigation

Towns of Tully and Lafayette
Onondaga County, New York

THE Chazen COMPANIES
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June 16, 2015

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EXECUTIVE SUMMARY

On behalf of the Onondaga Nation, The Chazen Companies (Chazen) presents a comprehensive framework of our present understanding of changing conditions in Tully Valley, including the mechanics and causal factors of the saline mudboils present in and along Onondaga Creek and their relationship to solution halite mining. Based on our review, we recommend specific approaches to manage the existing saline mudboils, to minimize the potential for formation of new mudboils, and to help mitigate other associated environmental hazards.

The Tully Valley is an elongate north-south valley backfilled by approximately 400 feet of glacial-era sediments. These sediments are underlain by more than 1,000 feet of limestone and shale, which in turn cover formerly-isolated halite (rock salt) beds. Available evidence suggests that, until halite mining began in the late 1880s, the Tully Valley watershed functioned as a stable stream valley with high rates of surface water runoff supporting Onondaga Creek, low rates of groundwater recharge due to the watershed's low-permeability clay and silt-based soils, and no interaction with the deeply covered rock salt. In the 1880s, the halite beds were discovered and intensive mining began, resulting in annual export of up to 1 billion gallons of brine during peak years and the eventual removal of approximately 1.4 billion cubic feet of rock salt.

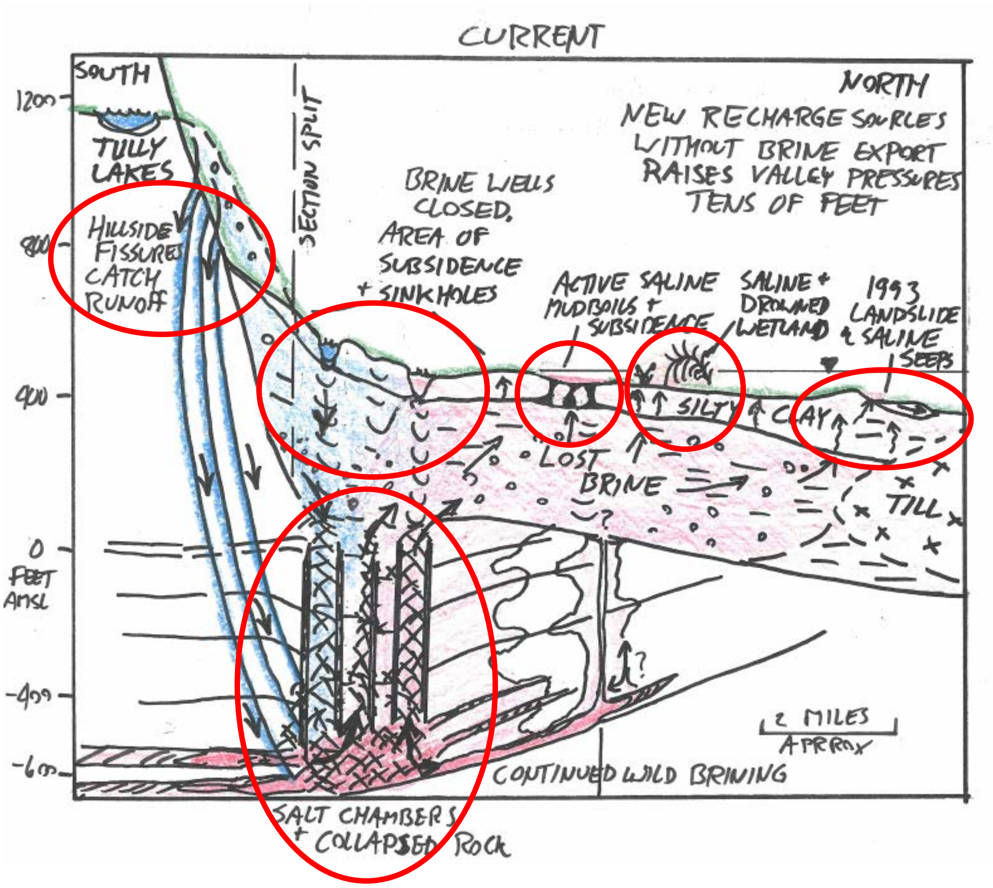
For most of the century of active mining, the salt mining industry used a "wild brining" extraction practice, meaning that water was injected into the salt formation and brine recovered with no effort to track, control, or provide sub-surface support to the areas mined. Initially, large volumes of freshwater were intentionally directed into the rock salt formation to dissolve the rock salt into a brine solution which could be exported to Syracuse. Up to 75% of salt deposits were dissolved out in some places, with resulting uncontrolled solution caverns being allowed to expand until overlying rock layers collapsed, leading to both broad land settlement and pockmarked areas with swarms of hillside fissures and numerous valley sink holes. As these fissures, rock collapse sites, and sink holes formed, uncontrolled stormwater runoff and shallow groundwater began cascading freely into the deep halite layers initiating further decades of yet less controlled brine generation. Throughout the century of formal brining operations, only an estimated 50% of the brine produced was recovered at the surface. The balance was never accounted for. Mining interests seemingly made no efforts – or made ineffective efforts – to control the rate or locations of their solutioning process or to manage migration of their lost brine. The lost brine, which continues to be generated and lost today, has been attributed to sharply rising groundwater pressures in the valley's sedimentary aquifer and to breaching of saline water at grade. Some of these breaches have taken the form of mudboils.

The saline Tully Valley Mudboils (TVMs) are one of the more unique features associated with the uncontrolled flow of lost brine. The TVMs have been described as "volcano-like cones of fine sand and silt that range from several inches to several feet high and from several inches to more than 30 feet in diameter" with "dynamic ebb-and-flow features that can erupt and form a large cone in several days, then cease flowing, or . . . discharge continuously for several years" (Kappel and McPherson, 1998). The first documented mudboil appeared in 1899, shortly after brine mining had begun. Over the intervening years, the number, intensity and salinity of mudboils in the Tully Valley increased dramatically. At present, the saline TVMs are a constant presence in the Tully Valley, influencing stream salinity and discharging tons of sediment to Onondaga Creek daily.

An extensive body of research has documented both the Tully Valley's solution mining history and its hydrogeologic setting, including the increasing salinity of mudboil discharges, the response of a Tully

Valley wetland to increased potentiometric pressures and increased salinity, salt contamination of domestic wells, and a 1993 landslide accompanied by saline spring discharges. Although at least one researcher maintains that early fresh-water Tully Valley mudboils may pre-date solution mining, the start date for limited freshwater mudboils is in fact immaterial since ample research establishes that the significant environmental harm experienced in Tully Valley over the past century including saline mudboils and changes to the water quality in Onondaga Creek are attributable to the valley's solution mining history.

The specific mechanisms leading to this environmental harm are depicted below in a drawing prepared by Chazen. Tully Valley's halite solution mining has caused structural geologic damage consisting of enlarged hillside fissures, sinkhole development, collapsed rock over solution cavities, and broad land subsidence. Overland flow and shallow groundwater now today continue to flow freely into the formerly-isolated deep rock salt formations, stimulating ongoing uncontrolled brine generation although formal halite mining operations have ceased, effectively perpetuating wild brining that maintaining today's elevated aquifer pressures under Tully Valley and unrelenting migration of brine upward toward the valley floor and Onondaga Creek. The uncontrolled brine emerges at grade not only in the saline mudboils, but also at salty seeps in wetlands, and in other seeps and springs in the nearby Tully Valley.

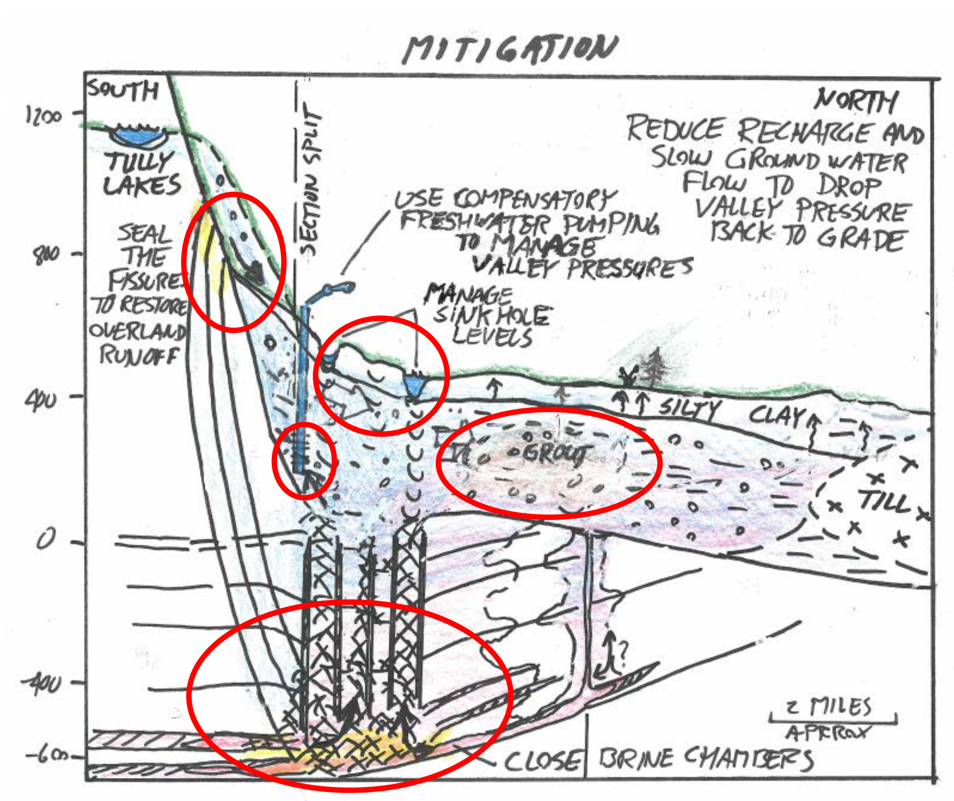


Addressing the cases of brine generation is necessary for any successful, long-term remedial investment of saline TVMs and associated impacts.

Two "end of pipe" efforts focused only on managing the silt load from saline mudboils have already been attempted. One sought to contain the silt discharges behind containment berms. The other sought to reduce the generation of silt by installing bypass wells through shallow sediments near the mudboil area so groundwater could emerge through pipes rather than mudboils and so entrain less sediment. Neither approach attempted to mitigate the salinity of the mudboils and each proved to be operationally short-lived. In addition, neither sought to address or prevent the development of additional saline mudboils, slow rates of salt brine generation, or relieve the root causes of the pressure relationships driving groundwater through the deep salt horizons.

These prior efforts have only made clear that such creekside approaches at best provided temporary sediment-loading relief into Onondaga Creek. "End of pipe" approaches cannot provide long-term mitigation since they do not retard or prevent the continued generation and discharge of uncontrolled brine.

Chazen therefore recommends moving to more comprehensive and permanent remedial investments. Our proposed remedies concentrate on reducing the entry of surface water into the deep subsurface so that brine generation slows and associated brine migration and pressure discharges driving saline mudboils, land instability, and wetland damage are curtailed. The specific recommended remedial approaches are depicted below and described thereafter:



Remedial Components:

- Stop surface runoff flows into hillside fissures. Do this by sealing or diverting runoff around hillside fissures which have opened as a result of solution mining. These today capture overland flow and should be sealed to return Tully Valley to pre-mining conditions when most precipitation did not penetrate the land surface to enter the salt horizons.

- Stop downward flow from sinkholes down into salt horizons. Some sinkhole management has already occurred. This effort should be maintained and expanded, ensuring that further surface water is diverted around sinkholes and by maintaining sinkhole water levels at or below adjacent shallow groundwater levels, as needed, so fresh water is not drawn downward.
- As a compensatory strategy, withdraw fresh groundwater from the valley's unconsolidated aquifer. Repairing fissures and controlling sinkholes may take some time. Compensatory extraction of freshwater groundwater from the overburdened aquifer will immediately help lower Tully Valley pressures and so slow mudboil discharges. Freshwater withdrawal wells should be located upvalley from the solution mining areas and can perhaps be phased out once the efficacy of sinkhole and fissure management mitigation is demonstrated.
- Seal the salt chambers. At least 17,000 acre feet (one football field X 2.4 miles deep) of void space reportedly remain below the valley floor. Sealing these open caverns and rubble-containing collapse zones either by isolating them or filling them will block freshwater entry and slow brine generation. This recommended action item could also represent an economically-viable disposal opportunity for a project involving placement of clean quarry fines or similar matter.
- Impede brine flow through unconsolidated sand and gravel with grout. The 400 foot thick sediments in Tully Valley consist of both porous sandy layers and less permeable silty clay. A geologic investigation is recommended to identify brine's preferential flow paths *en route* to the mudboils and springs. These pathways can then be grouted to constrain brine flow rates. Grouting must be performed in concert with the other recommended measures to avoid diverting brine break-out to new locations.

These mitigation strategies, focusing on blocking freshwater entry, cavern isolation, and brine pathway management, address and seek to repair hydrogeologic damage left by a century of industrial salt brine mining. Such actions are needed to reduce Tully Valley's persistent high groundwater pressure condition and to reduce volumes and rates of continuing brine generation. Doing so represents the only economically sustainable and long-term remedy to reduce the conditions driving the Tully Valley saline mudboils, mitigate other environmental harms, and correct water quality in Onondaga Creek.

1. INTRODUCTION

The Chazen Companies (Chazen) has been engaged on behalf of the Onondaga Nation to recommend remedial approaches for the saline Tully Valley Mudboils (TVMs). Chazen has reviewed much of the extensive record of documents and reports concerning the saline TVMs and on the basis of these available records has prepared this technical report for the Onondaga Nation.

This submission does not seek to argue with finality whether the phenomenon best described as the "saline Tully Valley Mudboils" pre-dates solution mining in the Tully Valley, although we believe it does not. Our review simply focuses on relationships demonstrating that salt mining under Tully Valley from the 1880s through the 1980s has been substantially responsible for the significant hydrogeologic, ecologic, and economic impacts observed both during and following the mining period. These impacts include not only saline mudboil discharges into Onondaga Creek, but also salty and pressurized groundwater harming wetland vegetation and destabilizing land in ways that in all probability contributed to a 1993 local landslide.

Our analysis and synthesis of existing documents presented herein indicate that control of saline TVMs can be achieved only by managing currently uncontrolled sources of groundwater recharge, brine generation, and brine migration associated with and continuing as a result of salt mining in Tully Valley.

2. GEOLOGY OF TULLY VALLEY

The Tully Valley is an elongate north-south valley backfilled by approximately 400 feet of glacial-era sediments. Beneath the valley sediments lie Devonian and Silurian era sedimentary rock formations which at depth include formerly-isolated halite (rock salt) beds. In the study area, the halite lies some 1,200 to 1,400 feet below the valley floor grade. All sedimentary rock formations in the area dip to the south and rise to the north. The halite beds under Tully Valley do not extend much further north than the former solution mining area and pinch out before they might otherwise be exposed at grade or come in contact with the sediments filling the Tully Valley.

In the immediate post-glacial period as ice wasted off the region some 10-15,000 years ago, the Valley was temporarily inundated by a glacial lake contained to the north by ice and to the south by the Valley Heads Moraine (Figures 14-16). Fifty to sixty feet of reddish silty clay were among the last sediments to settle in this lake before it drained, covering all deeper sediments. These deeper sediments include some coarser sand and gravel zones (Figures 1 and 15).

When the ice to the north melted away, the lake drained and isostatic rebound returned the land to its current elevation. During the post-glacial period, it is reasonable to assume that some land settlement and landslide activity occurred as saturated soils dewatered, land rebounded from under the weight of the glacial mass, and today's hillside grades were re-established. This period of greatest instability likely lasted in the range of a few thousand years.

All evidence suggests that once the valley's isostatic rebound slowed and post-glacial vegetation was re-established, and until rock salt mining began, the Tully Valley watershed functioned as a stable environment. The north-flowing Onondaga Creek was supported by relatively high rates of hillside and valley runoff due to the generally clayey hillside soils and silty-clay valley floor sediments. The high-runoff nature of the basin appears to have been acknowledged by the U.S. Army Corps of Engineers, which eventually constructed a stormwater flood control dam lower in this valley. The silty watershed soils also limited groundwater recharge, and all records suggest the halite beds deep below the valley were fully isolated from the surface environment and shallow groundwater until Syracuse's soda ash industry began drilling deep borings into the subsurface looking for salt deposits.

The pre-mining Tully Valley hydrogeologic setting is depicted in Figure 1 prepared by Chazen. Records reviewed by Chazen suggests that prior to solution mining, surface water and shallow groundwater in Tully Valley had no meaningful interaction with the halite located hundreds of feet below the valley floor. The salt horizons were separated from Onondaga Creek by approximately four hundred feet of mixed glacial sediments and many hundreds of feet of shale and limestone. Unlike the areas immediately surrounding Onondaga Lake, there is also no written or oral history of Native American, pre-colonial, or early American salt-related activity or awareness in the Tully Valley before brine mining began in the late 1880s. This is also evidenced by an absence of historic hamlet names suggestive of salt (e.g. Salina, Halina, etc.), historic topographic map features or names, or narratives reflecting an historic presence of salt in Tully Valley. Salt production prior to this time was focused only on the shores of Onondaga Lake as confirmed by ample written history, geographic reference points, historic maps, and other evidences of a salt-dominated environment.

The approximate locations of the two earliest salt exploration wells are also shown on **Figure 1**. Salt was identified only in the more southerly location; the salt evidently pinched off to the north since no salt was identified in this second boring area.

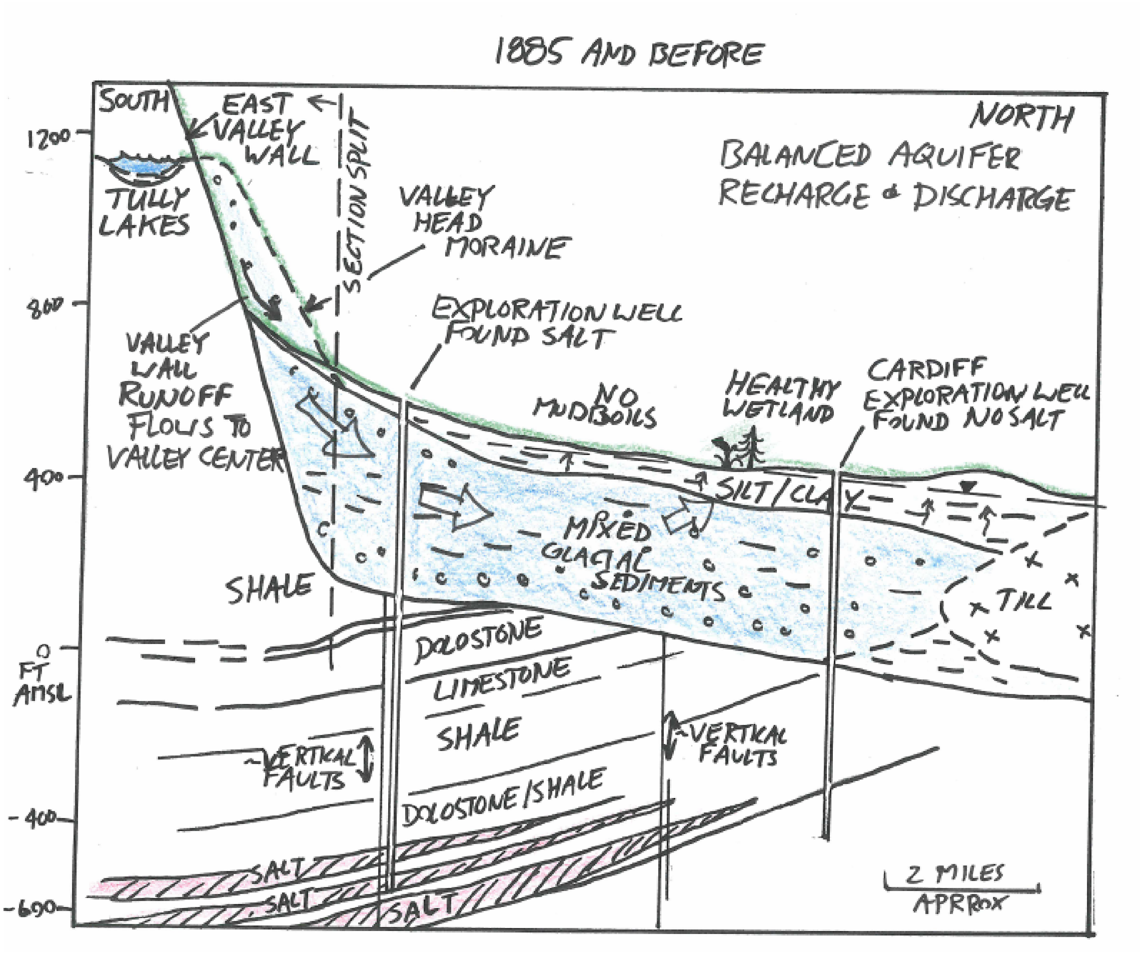


Figure 1. Longitudinal stratigraphic cross-section of the Tully Valley depicting its geology prior to initiation of solution mining of salt deposits. Figure prepared by Chazen.

3. HISTORY OF BRINE MINING IN TULLY VALLEY AREA

Once the subsurface halite beds were discovered, intensive brine mining operations began. Many tens of wells were bored into the halite over many decades to reach the salt. The first mining method selected to bring salt to the surface involved introducing freshwater into drilled wells where it would become brine that could be removed from adjacent boreholes once dissolved interconnections were established. At its peak up to 1 billion gallons of brine was removed annually from under Tully Valley, and after a century of operations approximately 1.4 billion cubic feet of salt had been removed from beneath the valley (Sanford, 1996).

The solution mining beginning in 1889 was initiated to supplement salt needed by Syracuse's soda ash industry. Once the deep halite layer was discovered, a brine export industry was quickly established in the Tully Valley. At first, fresh water was directed into drilled wells from the nearby higher-elevation Tully Lakes to dissolve the halite and generate brine. Because this water came from a higher elevation area, the freshwater entered the deep wells with enough pressure that brine flowed back up to the surface without needing to be actively pumped. This is shown on Figure 8.

The introduction of fresh water into the solid rock salt to manufacture brine dissolved out salt caverns. But the method was imprecise and industry records indicate that approximately 40% to 60% of the pressurized fresh water injected into the brining fields was never recovered (Larkin, 1950, cited in Sanford, 1996b). This means that for every gallon of brine removed to Syracuse, an equivalent volume of brine was lost below ground level, becoming a source of uncontrolled, lost, and pressurized brine. There seems to be little dispute among authors that from the 1890s forward such uncontrolled brine losses into the Tully Valley's subsurface continuously occurred.

The broader salt solution mining industry came to refer to this approach as “wild brining” or “blind brining” (as opposed to controlled brining), and the international solution mining industry recognized by the early 1900s the subsidence hazards associated with such brining methods (Sanford, 1996a). Sanford indicates that most other operators discontinued such practices by 1921, managing their brining operations instead with air-injection and other techniques to control and direct water movement in salt rock to create brine caverns with stable dimensions. Because such methods were never adopted in Tully Valley, however, lateral cavern expansion continued and roof rock either regularly settled or failed catastrophically.

The Tully Valley brine mining operations also failed to set any reasonable limits on the amount of salt removed in a given area. Whereas controlled solution mining practiced elsewhere sought to remove just 10% to 15% of rock salt to ensure that sufficient salt deposits were left intact to prevent land subsidence damage, the mining approach used in Tully Valley locally removed up to 75% of available salt in given areas (Shaffer, 1984, cited in Briggs and Sanford, 2000). A sketch of such wild brining and structural rock failure is shown in Figure 2. Industry consultants recorded that the total volume of rock salt removed from under the Tully Valley reached an eventual equivalent of 31,000 acre-feet by the late 1980s (CS Consulting Engineers and H&A of NY, 1992). This amount has been compared to 35 times the volume of the Syracuse Carrier dome.

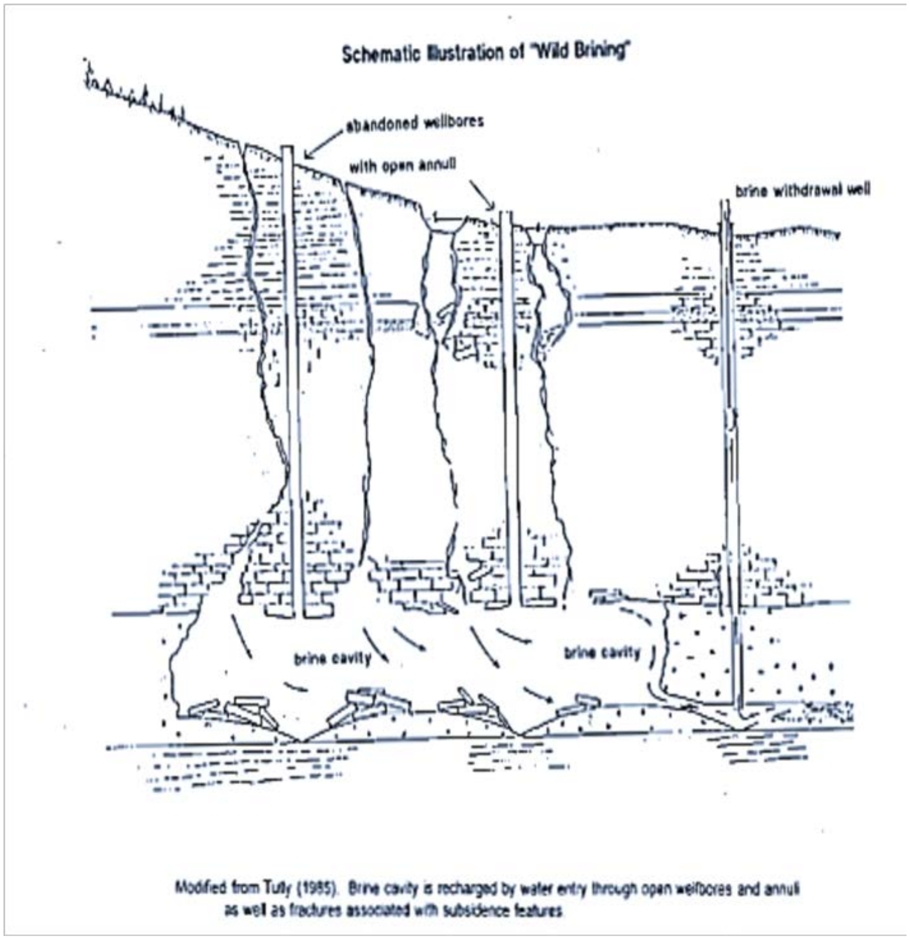
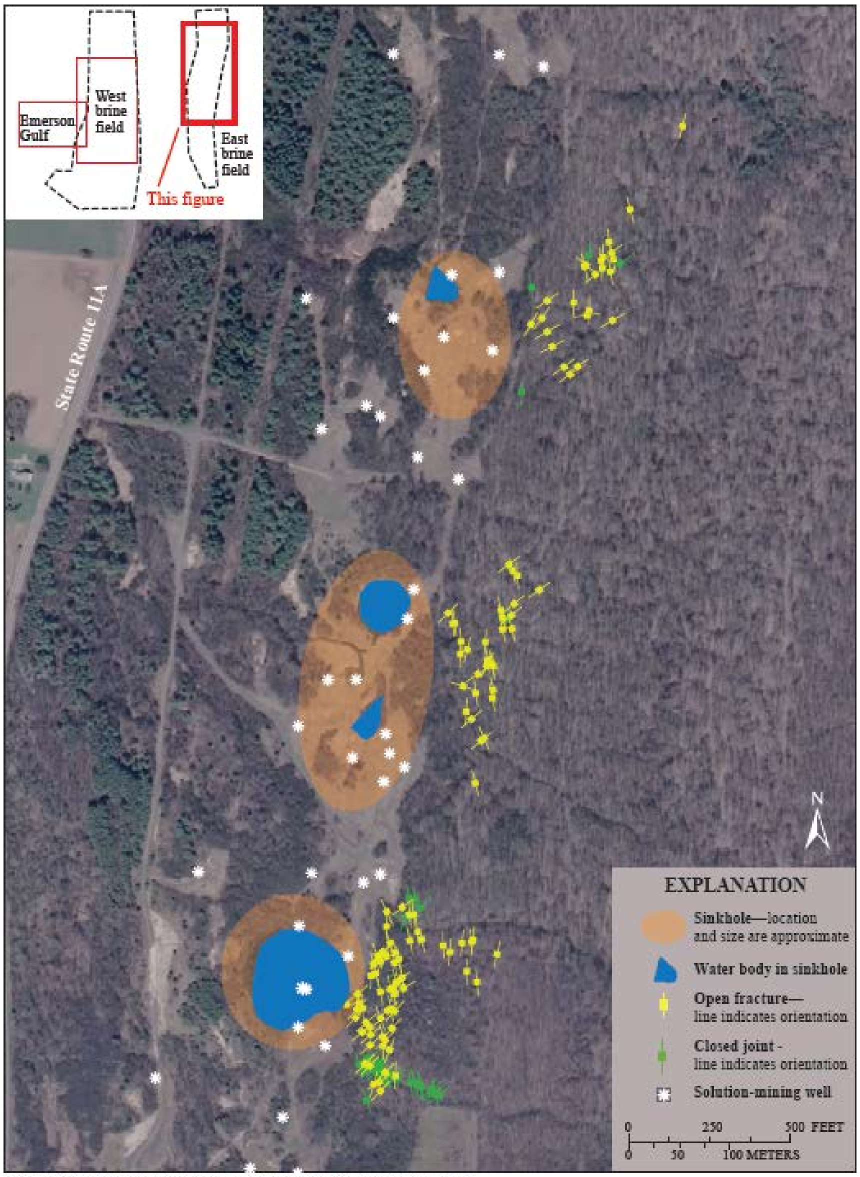


Figure 2. A sketch prepared by a consultant working for the Tully Valley mining industry demonstrating aspects of wild-brining activity (from Sanford, 1996a).

As caverns under Tully Valley expanded in largely uncontrolled directions, they eventually became structurally unstable, as shown above. Some overlying rock just settled in place resulting in area-wide land surface subsidence today measuring tens of feet. In discrete locations, vertical collapse zone or chimneys also developed, expressing themselves upward through to the valley floor as sinkholes. Finally, radial fracturing began extending outward as adjacent valley rock formations pushed into the deep salt caverns. These radial fractures are seen today as fissures on nearby hillsides (Figure 7 and related figures). With this level of bedrock damage, freshwater from overlying sediment aquifer horizons as well as hillside runoff could now flow directly into salt chambers, and the mining industry discovered that brine was being generated without the need to inject Tully Lakes water. Figures 8 and 9 show the transition between the early and later mining situations.

By around 1950, Tully Valley's halite mining operational area began to experience catastrophic collapse as up to 150 vertical feet of halite were dissolved in places out from under the limestone and shale cap rock (Kappel et all 1996). Sinkholes formed over some collapse zones and hillsides adjacent to the solution mining areas slumped, opening existing or new joints as deep vertical fissures (Hackett et al., 2009). Figure 3 depicts the distribution of hillside fissures (yellow) around former solution mining areas as well as rock collapse/sinkholes (brown and blue) around the former east brine field, as of the early

2000 field season (Hackett et al., 2009). These hillside fissures, tens of feet above the valley floor, diverted higher elevation runoff into the bedrock formation, providing a replacement source of high pressure groundwater recharge that allowed discontinued use of Tully Lakes water for brine mining. This new source of uncontrolled deep groundwater recharge contributed to brine production for decades, and as brine wells were sealed has continued brine generation still relieved at saline mudboils, wetland seeps, and noted as high pore pressures potentially associated with such land instability as the 1993 landslide.



North American Datum of 1983; Universal Tranverse mercator projection, Zone 18N;
Orthoimage base from New York State Office of Cyber and Critical Infrastructure Coordination, Spring 2006.

Figure 3. A map showing the spatial relationship between solution-mining wells and bedrock fissures in the east brine field of the Tully Valley (from Hackett et al., 2009).

A detail of the Figure 3 east valley wall study area is shown in Figure 4 as an oblique aerial site photograph. The fissures lie on a hillside that rises to the east of the sink hole on the valley floor.

Figure 4. Hillside fissures are visible in this leaf-off aerial photograph (from Hackett et al., 2009).

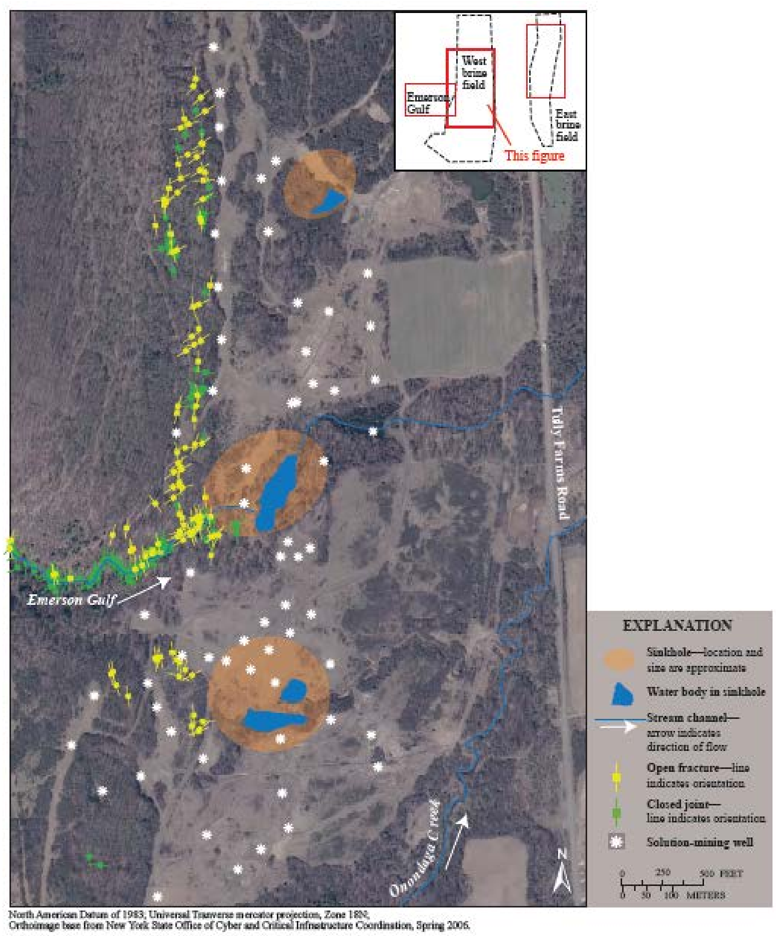


Figure 5. A map showing the location of bedrock fissures in the west brine field of the Tully Valley (from Hackett et al., 2009).

Similarly, fissures opened in the west Tully Valley wall near the former west brine field (Figure 5). Figure 6, drawn by USGS, depicts the relationship between collapsing roof rock over formerly- isolated halite rock formations, land settlement, sinkhole development, and the formation of hillside fissuring referred to as "tension bedrock fractures" on Figure 5. As demonstrated, the rock failed in columnar chimneys directly over solution cavities and also as radially-propagating fractures relieving the surrounding rock stress through existing or new joints extending up the valley walls. Chazen has added red, yellow, and orange flow lines to Figure 6 to show how hillside runoff (red) was captured by such fissures and sinkholes to recharge solution cavities (yellow) with the resulting generation of uncontrolled brine (orange) into the valley unconsolidated sediments. The figure helps show the relative elevation of hillside fissure above the valley floor. Examples of such existing fissures are easily visited and observed today, as shown on Figure 7.

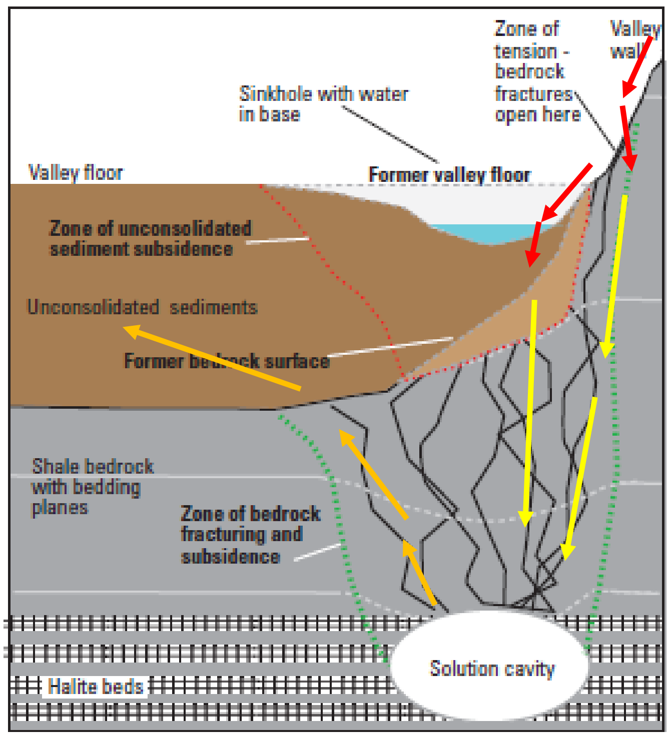


Figure 6. Sinkhole formation due to fissuring and collapse of solution cavities (from Hackett et al., 2009). This figure has been highlighted by Chazen, using red, yellow and orange arrows explained in accompanying text.

Figures 3 and 5 help begin to convey the scale of open jointing found today in Tully Valley's walls and valley wall stream beds. Fissures have opened both under hillside streams (Figure 7, right image) and across hillsides where they capture stormwater runoff (Figure 7, left image). By 1958-1959, Allied Signal, the company which was operating the Tully Valley brine mines at this time, realized it could now generate and export brine without formally injecting Tully Lakes freshwater at all; their brine generation practices were now fully supported by uncontrolled surface flows entering subsurface brining chambers through the fractured entry conduits developed during the early mining years. This is shown on Figure 9. Shallow groundwater was also noted entering salt caverns along failed and "closed" drill boreholes (CS Consulting Engineers and H&A of NY, 1992). The fact that such uncontrolled "wild brining" could not realistically be stopped, or that approximately 50% of brine generated in this informal manner continued to be lost into the geologic formation, appears never to have been addressed.

Figure 7. Examples of bedrock fissures in the Tully Valley hillsides (from Hackett et al., 2009).

Despite operational changes adopted by the broader salt solution mining industry and the documented adverse impacts occurring on the local landscape, this Tully Valley wild brining practice was continued without pause until the 1980s. The solution mine operators appear never to have had precise understandings of where fresh water entered the halite, how much generated brine was lost into the formation, where the lost brine was going, how large or where solution caverns were forming, or, quite importantly, how the industry might eventually slow or someday close down its brine mining process. It was clear, however, that lost brine was migrating upward into formerly fresh overlying aquifer horizons, evidenced by the provision of public water to local residents formerly using private wells, increasing salinity of mudboils over time, and tree ring evidence discussed below.

A characteristic of wild brining is that the most aggressive solutioning activity occurs where fresh water first contacts salt. When uncontrolled water sources are allowed to enter brining chambers, salt dissolution occurs in unknown and uncontrolled directions, propagating long distances “up salt” along salt bedding layers. Such “blind brining” solution channels have been recognized to extend at least a mile in some cases (Sanford, 1996b). In the Tully Valley, extensive blind-brined solution channeling is depicted on Figures 9 and 10, consistent with documented groundwater interconnections developed between the east and west Tully Valley wellfields (CS Consulting Engineers and H&A of NY, 1992).

In short, the wild brining history in the Tully Valley impacted the structural stability of the valley, the groundwater budget, and the rising potentiometric pressures associated with lost brine seeking relief. Importantly, relative to the central subject of this inquiry, these impacts were directly relevant to the persistence, frequency, and quality of the saline Tully Valley mudboils.

4. THE SALINE TULLY VALLEY MUDBOILS

The water quality of the earliest mudboils reportedly consisted of fresh water and silty clay. Much like a garden hose first discharges water contained in the hose before delivering refreshed water from the house, rising pressure generated by lost brine first resulted in mudboils that purged fresh aquifer groundwater before the mudboils began discharging salty water. Only as time passed did the TVMs began to exhibit their current salty geochemistry signature, which matches the deep brine solution salt composition as a finger-print associating brining activities with the Tully Valley mudboils.

Mudboils had been documented in scattered locations across the Tully Valley since at least the 1930s and appear to have been first referenced in print in an 1899 local newspaper, just a few years after solution mining commenced in the valley. Given that newspapers are generally interested in reporting unusual events and an absence of any known earlier mudboil references, this late 19th century publication suggests the valley had no prior history of mudboils. The 1899 publication is in any case the first known written record of a confirmed mudboil, occurring within the first 20 years of salt mining activity.

Tully Valley's mudboils are one of the most visually notable features in the region. USGS first described Tully Valley mudboils as "volcano-like cones of fine sand and silt that range from several inches to several feet high and from several inches to more than 30 feet in diameter" with "dynamic ebb-and-flow features that can erupt and form a large cone in several days, then cease flowing, or . . . discharge continuously for several years" (Kappel and McPherson, 1998).

A USEPA 2011 Compilation Report includes the following about the early condition of Onondaga Creek:

> *The Onondaga Nation Reservation, occupied continuously by the native Onondaga people since before colonization, is downstream of the mudboils. For untold generations, until only a few decades ago, the Onondagas' subsistence diet depended on protein from a variety of fish species, including brook trout (Beachamp 1908) salmon and trout (Jesuits and Thwaites 1896), eels (Bartram et al., 1973), and in the mid-20th century, bullhead, white fish, brown trout, rainbow trout, rock bass, suckers, as reported by Onondaga elders (Pearce, 1998). Other aquatic foods collected from Onondaga Creek and consumed by Onondaga have included crayfish, frogs, turtles, muskrat, and watercress (Pearce 1998). Onondaga Clan Mother, Audrey Shenandoah, reported that in winter time, the watercress was their only source of a leafy green vegetable (Pearce 1998).*
>
> *The Onondaga's subsistence use of the creek experienced a forced pause as suspended sediments and accumulation of sediments in the streambed altered or eliminated the food supply and its habitat (Pearce 1998). Onondaga Chief Irving Powless, Jr. recollected spear fishing in Onondaga Creek in the early 1940s when the water was so clear he was able to see fish on the creek bottom with only the light of a kerosene lantern. By the 1950s he observed muddy creek water "almost the color of chocolate."*

The transition from a historically clear Onondaga creek to turbid conditions generally coincides with the period in Tully Valley solution mining history when uncontrolled recharge was accelerating due to expanding hillside fractures and sinkholes. At the same time, some brine wells were being closed in the eastern wellfield area resulting in increasing subsurface pressure related to unrelieved brine generation.

The chemistry "fingerprint" linking the active mudboils and brine mining also became increasingly clear over time. The NYSDEC recognized this field situation when drafting a September 18, 1991 letter to the former mining entity, noting:

> *"that there may have been naturally caused, small, seasonal, freshwater mudboils, however, this historic environmentally benign mudboil activity must not be confused with the high volume, non-seasonal, saline mudboil discharges that have occurred at least since the early 1970s in the major subsidence area on Tributary 20B. The current and past mudboils at the Old Grist Mill and former Otisco Road crossing are "freshwater" discharges that have the geochemical signature of a fairly shallow, local, groundwater flow system. In contrast, the inception and activity of the high volume, "saline" discharges in the subsidence area coincides very closely with past changes in respondent's operating practices."*
> (quote from CS Consulting Engineers and H&A of New York, 1991)

Similarly, USGS acknowledges the increasing salinity as follows:

> *"Mudboil activity was intermittent from its first reported appearance in the 1890's until the 1970's (sic) when the rate of mudboil discharge and land subsidence began to increase. Historically, the water discharged from mudboils was reported as fresh, but chemical analyses in the 1970s indicated an increase in specific conductance and chloride concentration."*
> (Kappel et al., 1996)

Chazen's interpretation of the conditions observed by USGS and NYSDEC by the mid-1990s is that brine had begun reaching some mudboils mid-century while taking longer to reach others, thus the early references to both freshwater and briny mudboils. This changed over time as, one by one, all mudboils eventually became briny. Land instability and other impacts also became increasingly notable in the Tully Valley as decades passed. This was particularly true near the end of the 20th century when pressurized brine discharges increased as formal mining and the annual export of 1 billion gallons of brine ceased; the wild brining mechanisms delivering freshwater into the salt horizon were left largely intact aside from efforts to grout formal brine wells. In 1993, shortly after formal mining ended, the biggest landslide in centuries occurred, coincident with this period of high confined pressures in the valley. Brackish springs and "mudboil-like activity" were recorded in water seeps around the 1993 landslide margins (Kappel et al., 1996).

Figure 8, prepared by Chazen, depicts various aspects of solution mining conducted between 1888 and the mid-1900s, including the driving pressure created by diverting high-elevation Tully Lake water into deep solution wells, the resulting generation of brine, the development of rock failure zones in the mining area and adjacent hillsides, the effect of uncontrolled pressure losses into the valley geology, and the spread of lost brine estimated in the range of 50% of total formed brine into the environment.

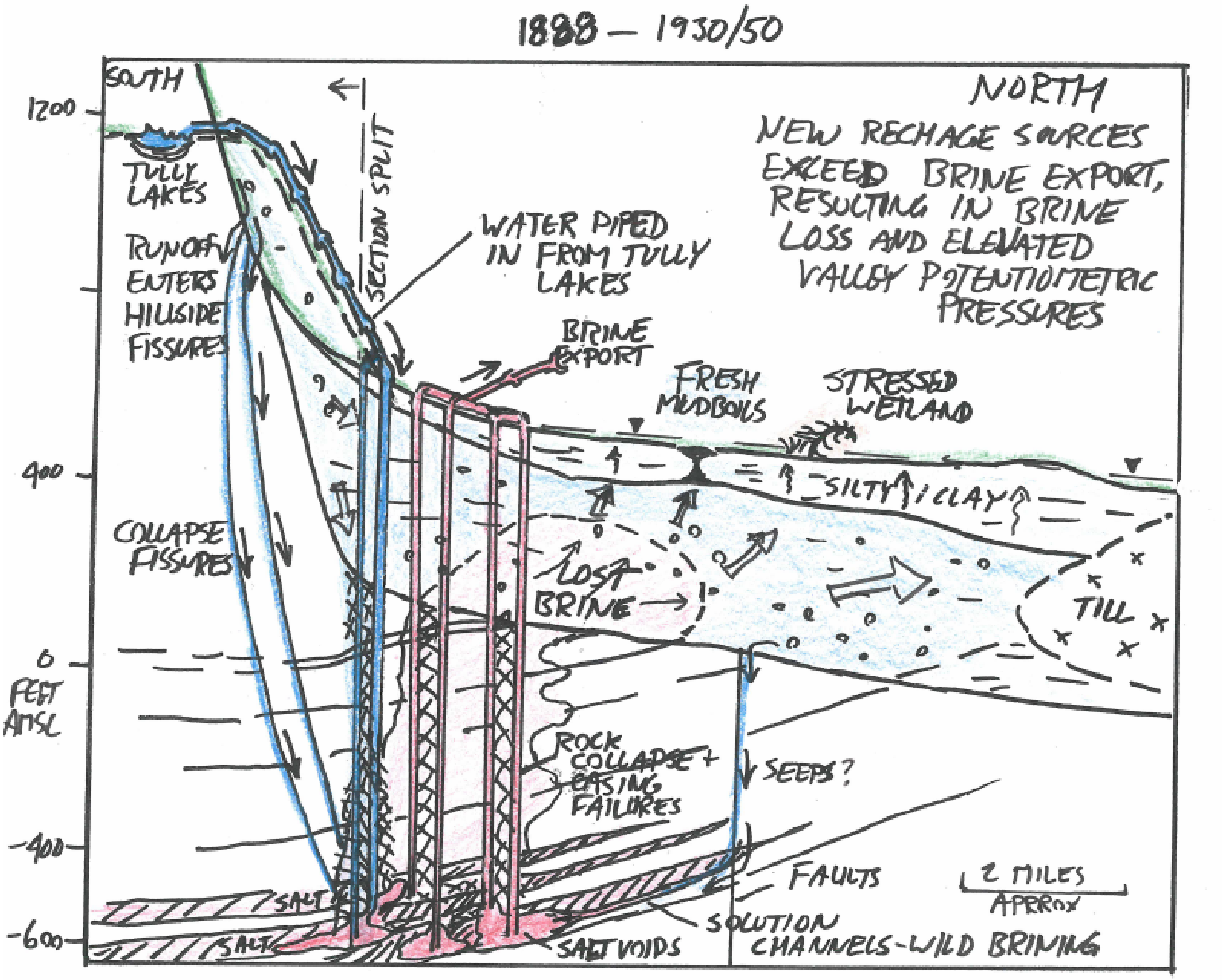


Figure 8. Schematic geological cross-section of solution mining of salt deposits in the Tully Valley between the late 19th century and middle 20th century. Figure prepared by Chazen.

Figure 9, also prepared by Chazen, summarizes aspects of the solution wild-brining activity engaged from the mid-1900s to the 1980s, after Tully Lake water was no longer needed to generate brine. This era was most notable for land subsidence, further sinkhole development, additional hillside fissures that captured valley runoff, and ongoing mudboil and seep activity.

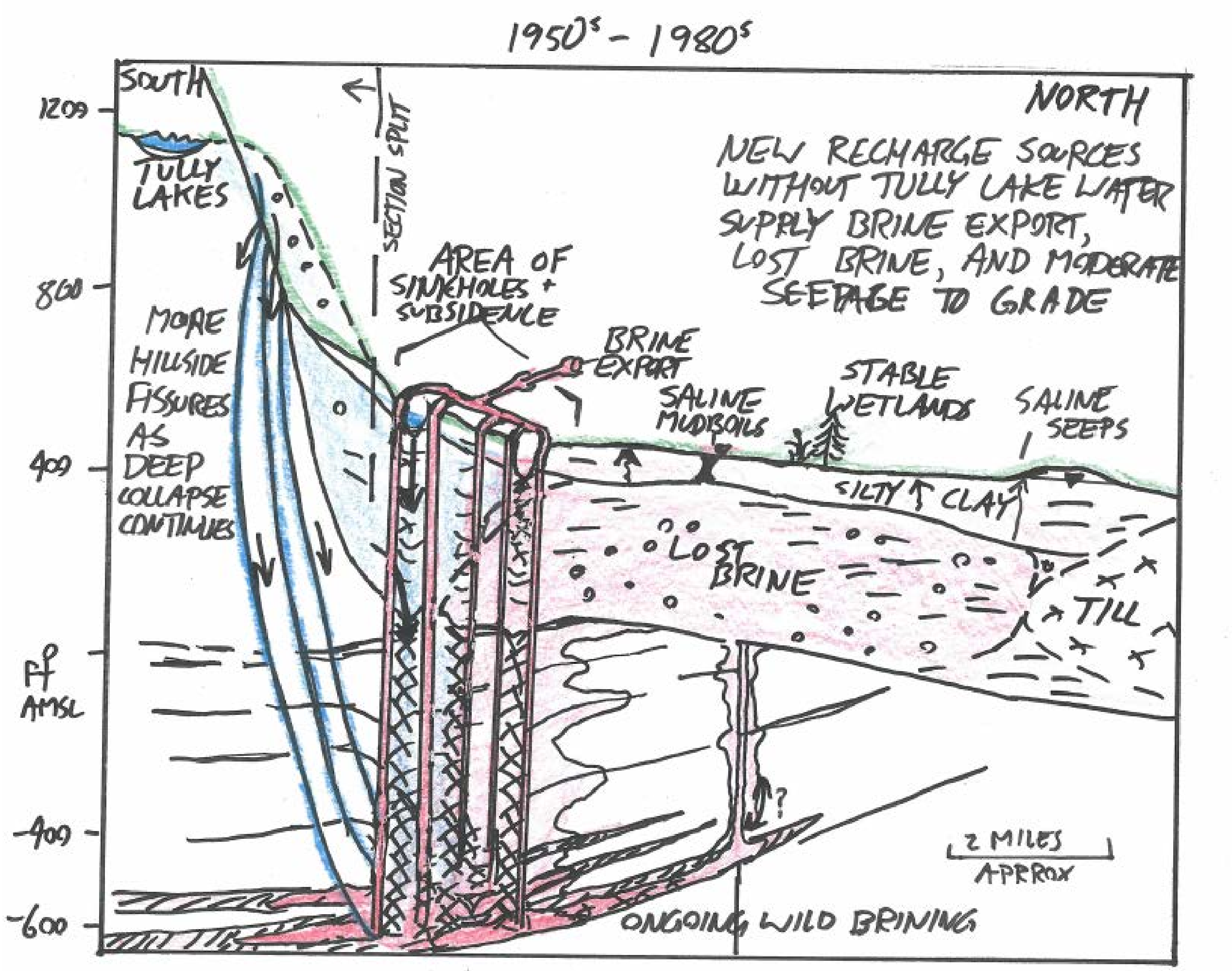


Figure 9. Geological cross-section depicting hydrogeological aspects of active solution mining in the Tully Valley reliant on uncontrolled freshwater propagation of wild brining. Figure prepared by Chazen.

Figure 10 summarizes various aspects of Tully Valley hydrogeology after the brine wells were capped. Capping took place over a number of years. First the east brine field and eventually all the brine wells were capped, ending in the late 1980s. The other sources of deep recharge to the salt formations through fissures, rock collapse chimneys, and sinkholes were, however, never sealed, allowing continued surface runoff flows into the salt rock formation. Various researchers documented sharp increases in potentiometric pressure in the 1970s and 1980s reaching as much as 70 feet above the valley floor as brine wells were sealed and formal industrial activity and the annual export of up to 1 billion gallons of brine ceased. Rates of brine discharge at mudboils accelerated around this time and the largest Tully Valley landslide in thousands of years occurred. Both events are reasonably explained by the excess groundwater pressures and uncontrolled brine migration left to continue indefinitely under Tully Valley as formal mining was discontinued.

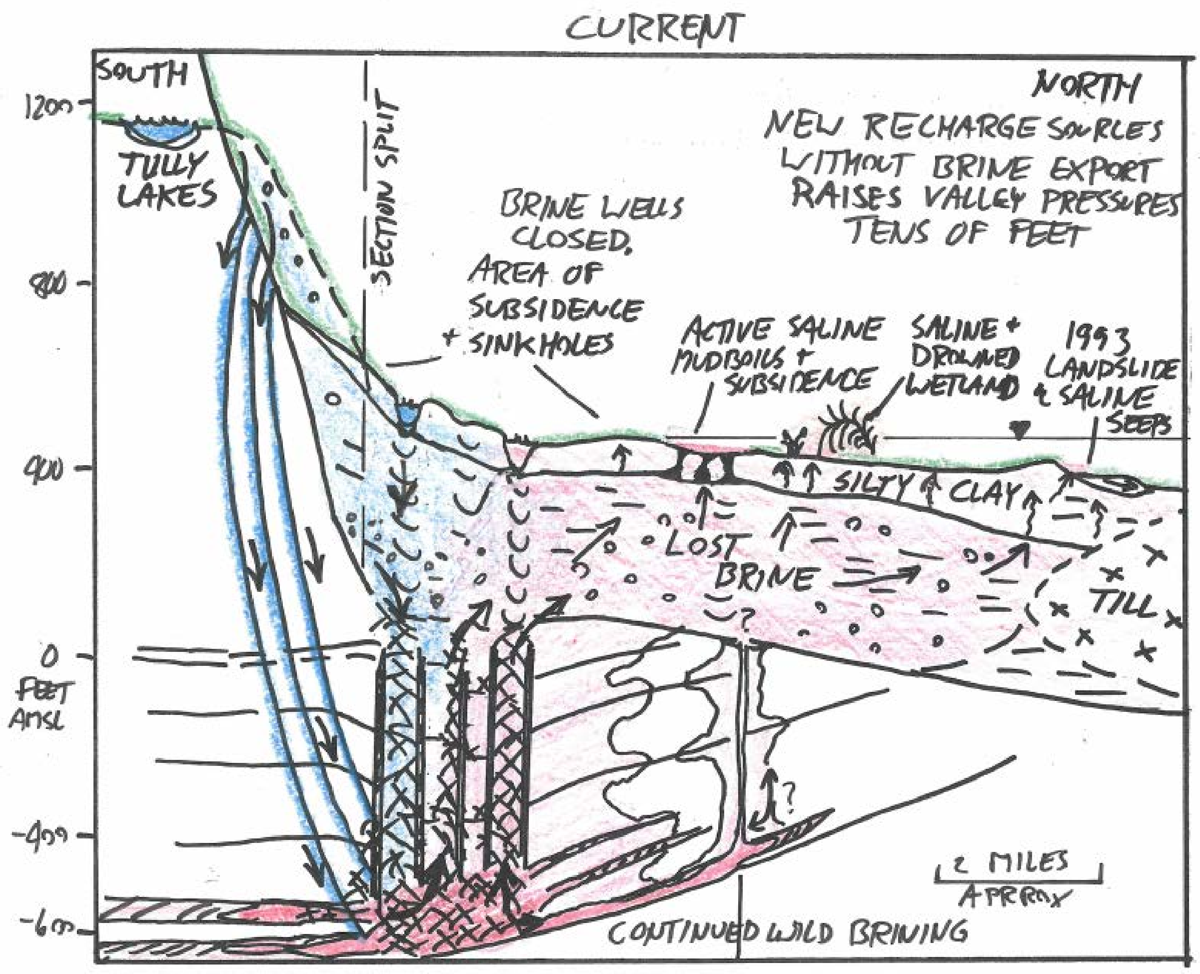


Figure 10. Geological cross-section depicting aspects of the hydrogeology of the Tully Valley after cessation of solution mining. Figure prepared by Chazen.

The USGS analyzed tree ring data from a wetland near the saline TVM site, exploring another line of data associated with the impacts of solution mining (Yanosky and Kappel, 1998). Healthy annual tree ring growth was evident prior to the onset of mining (Figure 11). Growth became suppressed as solution mining began until the mid-1900s, followed by a period of improved annual tree growth. Tree die-off then occurred in the late 1990s. The study also identified increasingly saline residues in the tree rings during the mining period, with the highest salt concentrations noted once formal solution mining operations ceased.

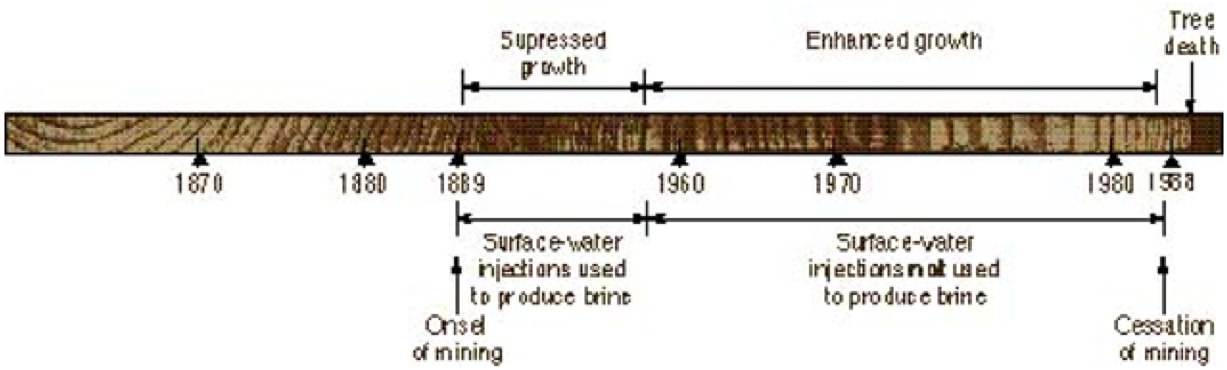


Figure 1. Photograph of core sample (1.5 x life size) removed from the oldest white pine that grew in the wetland. The tree died in late 1995 or early 1996. (Photograph by D. Usher, USGS)

Figure 11. A tree-ring record from a Tully Valley wetland showing growth changes corresponding to changes in the hydrogeology of the site (from Yanosky and Kappel, 1998).

This tree growth record was interpreted by USGS to reflect the hydrogeologic regime changes associated with solution mining phases (Yanosky and Kappel, 1998). The pre-mining period was associated with healthy wetland vegetation. Wetland tree growth was then retarded as induced pressures generated by Tully Lake water injections caused upward pressures resulting in root zone saturation that stunted (effectively drowned) tree roots. Healthier growth resumed as Tully Lake water injections stopped and the inflows of shallow groundwater and hillside runoff via fissures and sink holes drove brine generation, bringing brine removal and generation seemingly into closer pressure equilibrium than previously. But as brine removal wells were capped, tree growth again became stunted and complete wetland die-off subsequently occurred, attributed both to sharply raised potentiometric pressures and increasingly salty seeps. When annual removal of approximately 1 billion gallons of brine stopped while the inflows of fresh water to the saline rock caverns remained unchecked, this resulted in a 70 foot rise in the unrelieved hydraulic head in the semi-confined valley aquifer and the continued displacement of brine toward ground level including this study wetland (Kappel, 1992).

Other researchers also noted transitions in groundwater chemistry over time, with mudboils first reflecting salt-free sand and gravel and bedrock geochemistry (Getchell, 1983), transitioning to geochemistry matching that of the deep halite brine (e.g. Baldauf, 2003). Domestic wells in the Tully Valley were rendered unusable by brine during this time period, with particularly high salt contamination reported by residents after closure of the wellfield (Bergmeier, 1998). Electrical conductivity measurements presented in Figure 12 represent a surrogate for dissolved salt content recorded by USGS, documenting steadily-rising groundwater salinity in the mudboil vicinity.

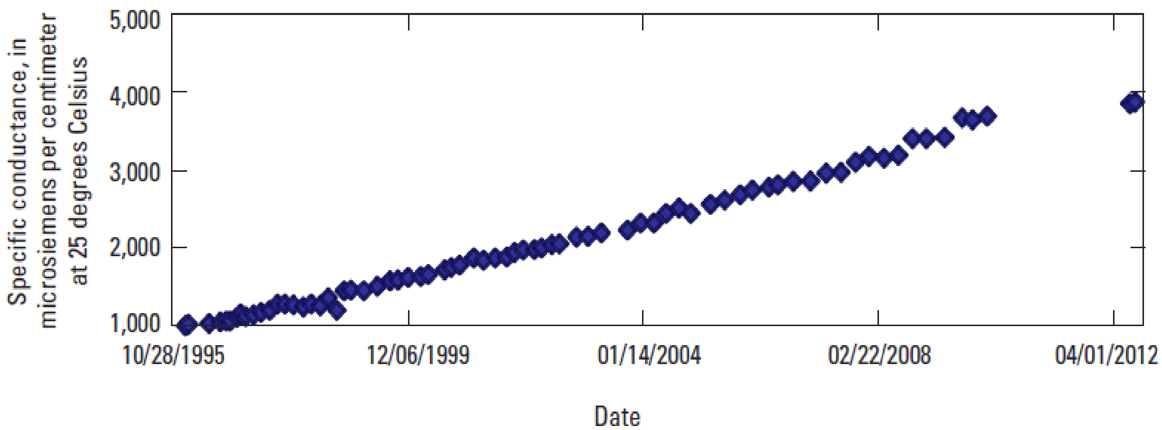


Figure 12. Graph of specific conductance measurements for groundwater from a well in the Tully Valley (reprinted from Kappel, 2014).

Figure 13 below (repeated from Figure 10), summarizes again the current geologic damage associated with uncontrolled wild-brining which persists today in the Tully Valley. The higher-elevation sources of groundwater recharge at hillside fissures and higher-elevation sinkholes are evidently sufficient to sustain the pressures noted near the mudboils, at the drowned wetland, and likely in the landslide area.

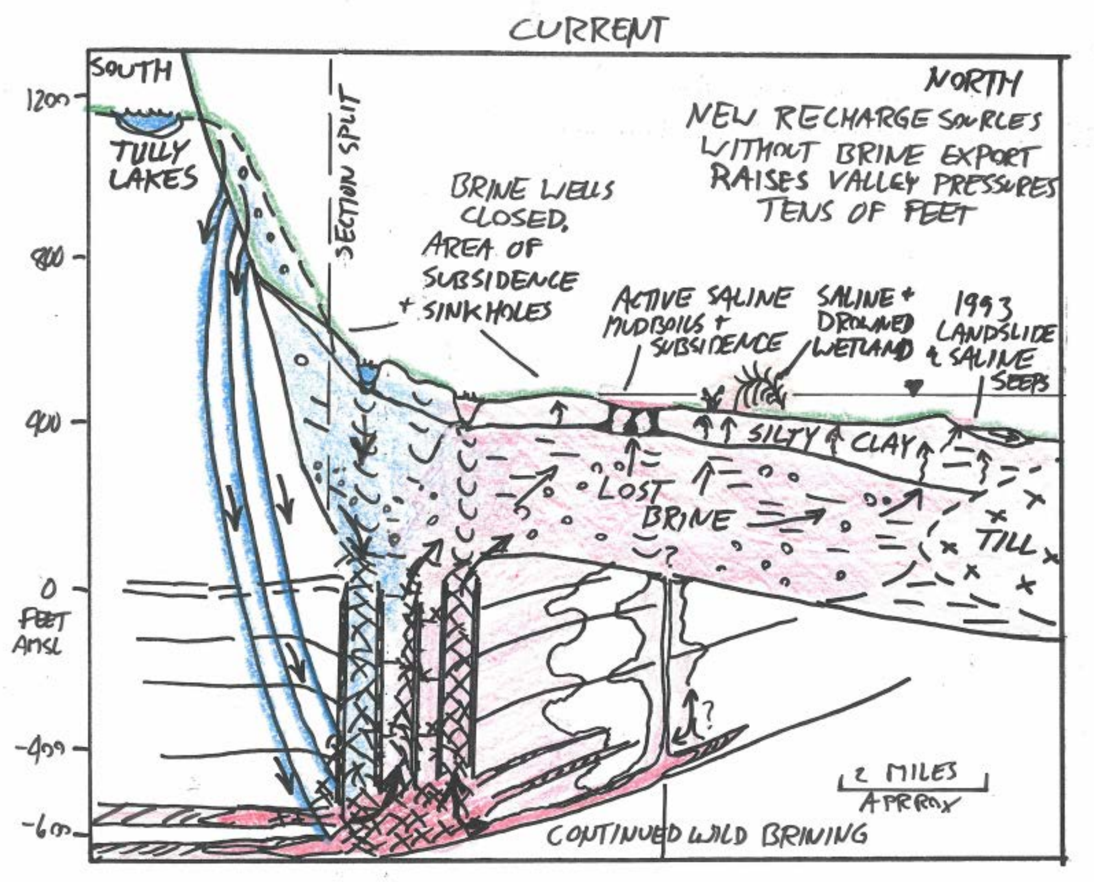


Figure 13. Geological cross-section depicting the current hydrogeology of the Tully Valley. Figure prepared by Chazen.

As of 2000, subsidence was being recorded as far as 2,000 feet from former solution mines (Briggs & Sanford, 2000). By 1992, approximately 9,000 acre-feet of land settlement had been documented, with 17,000 to 22,000 additional acre-feet of known void space recognized by an industry consultant to remain below grade (CS Engineering Consultants and H&A of NY, 1992). This 1992 estimate of remaining void space was based on the documented export of 31,000 acre-feet of salt from Tully Valley over the century of active mining less the measured amount of land settlement and estimated rock bulking. We believe this estimate of subterranean void space fails to acknowledge additional void space created by the production of lost brine never captured by the mining industry. It also ignores the more than 20 additional years of wild brining has occurred since the 1992 study. Thus it is reasonable to estimate that today's volume of subsurface void space may be as much as double the 1992 estimate.

In summary, uncontrolled hydrogeologic factors of concern associated with saline TVMs remaining in Tully Valley today include:

1. Hillside rock fissures today continue to admit water into the bedrock environment. The elevation of these fissures is sufficient to explain the pressure elevation conditions recorded in the Valley including near the saline TVMs. The precise volume of water surcharged via these fissures has not been confirmed but an industry consultant reportedly documented increases of groundwater recharge through such subsidence-induced fractures (Tully, 1985, cited in Briggs and Sanford, 2000), although Chazen has not seen the referenced study. It is not difficult to understand that where hillside soils previously admitted scant inches of annual recharge, today all runoff enters fissures to surcharge the deep geologic formations.
2. Sinkholes also remain important conduits for surface water to enter the bedrock or deep groundwater environment. Significant effort has been committed to controlling surcharges entering sinkholes. If runoff still enters any uncontrolled sinkholes, or whenever water elevation in sink holes rises above adjacent shallow groundwater levels, surface water may still be recharging the deep groundwater environment.
3. Shallow groundwater also contributes to overcharging of the deep rock formations. A share of shallow groundwater was recognized by industry consultants to be cascading down into well boreholes during periods of active mining, documented by lowered potentiometric levels recorded in adjacent overburden wells (CS Engineering Consultants and H&A of NY, 1991). To the degree that this is still occurring, overburden movement of groundwater may still be reaching great depths.

Neither fissure interception of runoff, stream capture, sinkhole loading, or shallow groundwater penetration to depth existed prior to solution mining. Until rock chimney collapse pathways connected the unconsolidated sediments in the Valley with halite and until hillside fissures allowed runoff to do the same, there were negligible or no pathways for shallow groundwater or runoff to encounter salt. But today, these pathways remain as a result of mining-related geologic damage and facilitate continued wild brining and the persistence of elevated pressure across the valley floor.

It is these unmitigated solution mining pressures which drive today's unrelieved saline TVMs. When the last solution mine well was capped in the late 1980s and efforts to grout industry wells ended, the freshwater entry sources and uncontrolled vertical recharge pathways remained in place. Pressures spiked in observation wells as much as 70 feet above the valley floor, rates of mudboil discharge increased, wetland trees experienced both root drowning and sharp increases in salt exposure, and the 1993 landslide occurred, all reflecting an unbalanced environmental pressure and salt spreading condition. The best way to describe the current situation may be to recognize that brine effectively continues to be produced today even though the product is no longer being accepted by the industry, resulting in pressurized and unwanted brine emissions throughout the valley.

5. DISCUSSION

This section contains extended discussion and provides more documented evidence supporting prior sections. Section 5.1 provides more history of solution mining activities. Section 5.2 provides more documentation of mudboil activity and salinity. Section 5.3 explores why mudboils are situated somewhat north of the former solution mining wells. Finally, Section 5.4 reviews some alternate or early mudboil explanations. If desired, this entire section may be viewed as meta-data and potentially skipped, leading the reader directly to remedial recommendations in Section 6.0.

The saline TVMs appear akin to a “flowing sands” phenomena sometimes encountered during well drilling or soil borings when a confining or semi-confining layer overlying a deeper water-bearing unit under pressure is penetrated. Once a flow channel through the confining/semi-confining layer is created, pressurized water flows upward seeking pressure equilibration. Based on the turbidity exhibited in Onondaga Creek for many decades, upward pressures in the Tully Valley have transported significant quantities of suspended materials to the surface, resulting in extensive land subsidence around the emission areas. Although globally there are several other documented types of naturally occurring mudboils, they are commonly associated with geothermal activity or permafrost, which renders their mechanics substantially different than those observed in the Tully Valley. The saline TVMs are essentially intermittent high pressure springs, which are driven by nearby sources of higher elevation groundwater recharge passing in proximity to brine mining rock horizons.

Chazen’s review of the available information indicates that the saline TVMs were created by changes to local hydrogeologic conditions associated with solution mining in the Tully Valley. Corrective measures needed to manage the saline mudboils and additional physical and ecological damage occurring in Tully Valley should acknowledge and address the on-going wild brining that is only otherwise leading to further valley settlement into ever expanding solution mining caverns.

5.1 Brining History

A step by step history of brining activity in the Tully Valley is provided below. The more integrated description was provided previously in Section 3.

Solution mining began in 1889 by intentionally diverting water from the nearby Tully Lakes into a network of brine wells drilled into the formerly isolated salt rock horizons more than a thousand feet below the valley bottom. The freshwater became a saturated brine when it contacted the rock salt. The pressure on the brine maintained by the Tully Lakes water flow was high enough that about half returned to grade to be delivered by gravity-flow through pipes northward to Syracuse for industrial use. Substantial brine was also lost in the geologic horizons resulting in heightened local area groundwater pressures and salt water aquifer pollution. As rock salt was dissolved, particulate debris settling in the growing cavities limited freshwater contact with the chamber bottoms, resulting in ever-widening solution caverns.

NYSDEC and AlliedSignal have each recognized without dispute that “wild-brining” solution mining was practiced for decades in the Tully Valley. Wild brining is generally acknowledged as a potentially damaging practice which can result in exactly the kind of uncontrolled expansion and increased instability seen in and around the Tully Valley brine mining areas. The resulting land settlement, sinkholes, rock collapse zones, and hillside fissures described elsewhere eventually allowed uncontrolled entry of fresh overland flow and fresh groundwater directly into the rock salt horizon. The rates of brine formation became so great over time that, when some of the solution wells were closed in the second half of the 20th century unrelieved brine pressures built up under the semi-confining sediments and saline TVM emission rates increased.

In general, the processes that led to vertical and pressurized connections between deep rock salt and formerly fresh water in the Tully Valley stream and shallow glacial sediments include the following:

- Beginning in the 1880s, water from Tully Lakes was directed into solution boreholes to create brine solution and to create a sufficient upflow pressure to drive brine solution back up to the land surface and into a gravity pipe flowing to Syracuse.
- Solution mining well casings were not all grouted, allowing uncontrolled groundwater to flow into salt rock horizons.
- Of all water introduced, industry reports suggest only approximately 50% of injected water was recovered as brine. The rest of the water seeped in an uncontrolled fashion into surrounding geologic formations as lost brine, providing the first stage of over-pressured salty water spreading into deep geologic formations.
- Industry records indicate that, in some areas, as much or more than 75% of the local salt formation was removed (in excess of 1.4 million cubic feet or 35 times the volume of the Carrier Dome), resulting in caverns estimated to vary in vertical depth from 25 to more than 300 feet.
- In the 1920s, as brine wells failed occasionally, uncontrolled local groundwater flow was recognized to be flowing down into solution mining depths along the outside of injection well casings or through penetrations with no remaining casings. This phenomenon added local groundwater to the Tully Lake water used to generate brine.
- During this time period that uncontrolled solution mining was becoming recognized within the industry as “wild brining” or “blind brining.” This practice was largely discontinued elsewhere around this time in industry history as it became recognized that uncontrolled brining led to solution channel formation in unexpected locations and directions.
- The most aggressive solution activity generally occurred where the freshwater first encountered salt, thereby rapidly expanding solution channels around any location where freshwater might seep into a deep rock salt zone as a result of a rock failure. This phenomenon tends to exacerbate outward migration of solution channels, widening the “mined” areas rather than maintaining a small geographic footprint of solutioning.
- Roof rock collapses from over-widened rock salt solution chambers resulted in land subsidence. Sink holes and hillside fissures also began to form, creating additional vertical groundwater and surface water communication pathways.
- White pines in a wetland north of and more distant from the solution mining area than today’s mudboils experienced suppressed growth rates between 1890 and 1960. This growth limitation was attributed by USGS to high groundwater pressures (e.g., raised water table) correlated to uncontrolled pressure generated by the solution injection mining process and the associated loss of up to half of the freshwater introduced to the deep subsurface. Tree growth resumed healthy patterns from approximately 1960 to 1980 when active freshwater injection was fully phased out and brine generation was driven by uncontrolled groundwater entry from overlying formations and runoff captured by hillside fissures. During this period, uncontrolled freshwater entry appears to have been somewhat matched by the rate of brine export, thus partially reducing the pressures generated by brine lost in the solution mining vicinity. Tree growth then

declined again followed by tree death when pressures rose sharply as brine wells closed in the 1980s. Brine had reached the wetland, as evidenced by tree rings showing increasing levels of chloride deposition.

- During the 1940 and 1950s, solution mining areas expanded and extensive land subsidence was noted as expanding solution caverns began settling broadly or collapsing catastrophically. Sinkholes formed over significant rock layer collapse zones. Hillsides above the solution mining areas slumped inward slightly, opening existing joints in the bedrock valley walls visible as deep vertical fissures. Hillside overland flow formerly going to Onondaga Creek entered the deep subsurface via these hillside fissures and where joints opened under existing streams, both stream flow and hillside runoff cascaded into deep rock horizons, all able to contribute to wild brining activities.
- By 1958-1959, the infiltrating recharge volumes from the failed well columns, sink holes, hillside fissures, and land subsidence became sufficient to allow discontinuation of Tully Lakes water injections. The alternate freshwater sources maintained sufficiently high upward pressure conditions to continue driving brine to the heads of the solution wells (Yanosky & Kappel, 1998).
- From the 1950 through the 1980s, continued and expanding wild-brining resulted in further land subsidence, roof rock failures, sinkhole development, and hillside joint expansion.
- Extraction from the east brine field terminated in 1960. Capping the pressurized wells caused recorded increases in area-wide groundwater pressures. Brine removal persisted in west wall brining locations (Yanosky & Kappel 1998), so some pressure relief was maintained by brine removal in those Tully Valley areas.
- When Tully Valley solution mining stopped entirely, the annual removal of approximately 1 billion gallons of brine ended. This transition, which occurred in the late 1980s, caused the hydraulic head in the deep sand and gravel zone to increase by 70 feet or more. This change coincided with the onset of increasingly severe mudboil activity and changes in the quality of water discharged from the mudboil area (Kappel, 1992) and presumably the communication from NYSDEC noted on page 16.
- Between 1988 and the present, recharge factors remained largely unchanged, except that 167 boreholes have been grouted and some sinkholes have been filled or partially drained in an effort to limit direct runoff-entry to the deep salt rock horizons. Hillside fissures, open deep halite caverns, and some sink holes remain, and the continued discharge of saline TVMs confirms an ongoing wild-brining condition today. The cessation of brine extraction correlated with sharp increases in groundwater pressure and wetland mortality once recharge surcharges were no longer relieved by brine well use (Yanosky & Kappel, 1998).

As indicated above, solution mining has substantially altered the hydrogeologic regime of the Tully Valley in ways that significantly and, thus far, permanently diverts overland flow into deep geologic formations via sink holes and hillside rock fissures. These changes essentially allow wild brining to continue and, because the brine product is no longer exported to Syracuse, maintain significant pressure within the geologic bedrock and overlying sediment formations. Because land elevation falls to the north, the contained pressures end up to tens of feet above the valley floor in areas near the saline mudboil area. Briggs and Sanford (2000) have each recognized that hydrologic impacts of solution mining in Tully Valley increased water pressure to the groundwater system. Such pressures near the mudboils are also noted by USGS (Kappel and Miller, 2005).

5.2 Mudboil Emissions and Water Quality Changes

Several studies document changes in water quality occurring in ground water wells and mudboils in the Tully Valley. For example:

- Getchell (1983) indicated that early mudboil emissions matched the chemical signature of displaced water from the sand and gravel and from underlying shale and limestone in the valley.
- Of later mudboil emissions, Getchell & Muller (1992) wrote that "[t]he water source of the King farm effusion [mudboil] is not shallow" and demonstrated the similarity of mudboil water quality with groundwater in the halite in the Syracuse formation under the valley. By 1980, chloride concentrations were approximately 350 mg/L and sodium was 250 mg/L.
- Kappel & Miller (2005) also confirmed that the chemical signature of the saline water is consistent with the ground water in the halite in the Syracuse formation rather than groundwater from any deeper formations known to exist under the valley.
- Kappel (2014) has documented nearly two decades of increases in electrical conductivity of saline emissions and presence (see Figure 12).

In addition, various teams of investigators have consistently confirmed the saline signature of the mudboils:

- Kappel and Miller (2005) document emissions at approximately 1.0X the salinity of seawater.
- Kappel et al. (1996) reported that mudboil discharges became saline around the 1970s
- Yanosky and Kappel (1998) detected increasing concentrations of salt residues in white pine growth rings north of the mudboil area.

All evidence suggests early mudboils were not salty, but became salty over time as brine lost from the wild-brining activity moved outward including toward the TVMs. The lost brine is thus understood to have pressed upward, through the overlying bedrock formation, then into the deepest sand and gravel formations, and finally up through the semi-confined late-glacial lake silty clay horizon.

The mudboil salinity is an effective tracer, linking mudboil and likely all other valley saltwater discharges to brine from solution mining activities in the deep halite formation under the valley. The decades which passed before brine reached the ground surface allowed long periods during which other theories about TVM source water were also being explored. Once salinity matching that of the deep salt rock formation was detected in the increasingly saline TVMs, however, the chemical finger-print of solution mining and the saline TVMs and helped rule out other explanations for these phenomena. Recent geochemical analysis by Baldauf (2003), Curran (1999), and Epp (2005) continue to confirm similarity of the mudboil geochemistry with that of the halite formation at depth.

5.3 Location of Mudboils

Mudboils and other similar features including seeps and springs occur where underground water pressure is relieved at grade. Mudboil locations recognized by USGS as the Mudboil Corridor are shown on Figure 14, extending approximately one mile south-to-north from the north margins of the solution mining areas nearly to the 1993 landslide (LS-4) site (Kappel et al., 1996).

Multiple factors explain why mudboils associated with solution mining occur only north of the solution mining area, as follows:

- The elevation of the valley falls to the north, dropping the land elevation below the semi-confined pressure line. This is represented on Figure 13 by the horizontal line with a small black triangle, which depicts the approximate potentiometric pressure level. Only to the north, within the central Tully Valley, dues this pressure plain exist above grade. This is the dominant reason why saline TVMs, a damaged wetland, and soils with high pore pressures are found north of the solution mining area in Tully Valley.
- "Blind brining" can extend solutioning at least a mile (Sanford, 1996b) beyond freshwater injection locations. This reasonably extends the reach of uncontrolled solution-opened pressure channels significantly toward or even under today's mudboil area. No such solution channels have been confirmed, however, hillside fissures correlating nearer to the solution mine area with halite cavern failures at depth have been noted at least half-way to the mudboil area (Figure 1 in Hackett et al., 2009), suggesting some presence of northward solution cavities.
- The area's bedrock geologic formations rise to the north and the valley floor descends to the north, so less bedrock covers the rock salt north of the former solution mining areas. The rising formation brings the buried bed salt and associated solutioning chambers, collapsed areas, and wild brining flow channels closer to grade in the direction of the saline TVMs. These relationships are evident on Figure 1.
- The thickest buried ice-contact deposits lie near the saline TVM location (Figure 15 at cross section E-E'). Buried ice contact deposits, usually consisting of coarse sand and gravel, would facilitate preferential brine migration. Cross section E-E' itself, published in Kappel & Miller (2005), not reproduced here, also indicates thinning of the semi-confining silty-clay sediments near the valley center in this area, altogether rendering the current mudboil location as a potential zone where brine can readily breach through the semi-confining horizons.
- A significant volume of glacial till is recognized by USGS further north (Figure 15 at section D-D'), likely barring any further northward migration or relieving of pressurized lost brine.
- Finally, structural analysis suggests the presence of several east-west bedrock lineaments crossing the Tully Valley. One may associate Rattlesnake Gulf with Rainbow Creek. Another lineament reportedly coincides with the salt mining area. Both are shown conceptually on Figure 1, although the extent of vertical or lateral movement along these lineaments is unknown. The current location of saline TVMs could potentially be influenced by such lineaments, but only if wild-brining solutions followed halite beds as far north as the Rattlesnake/Rainbow lineament, such that upvalley pressures could then drive saline water upward to overlying sediments. The potential influence of these structural elements are shown on Figure 1 and Figures 8-10.

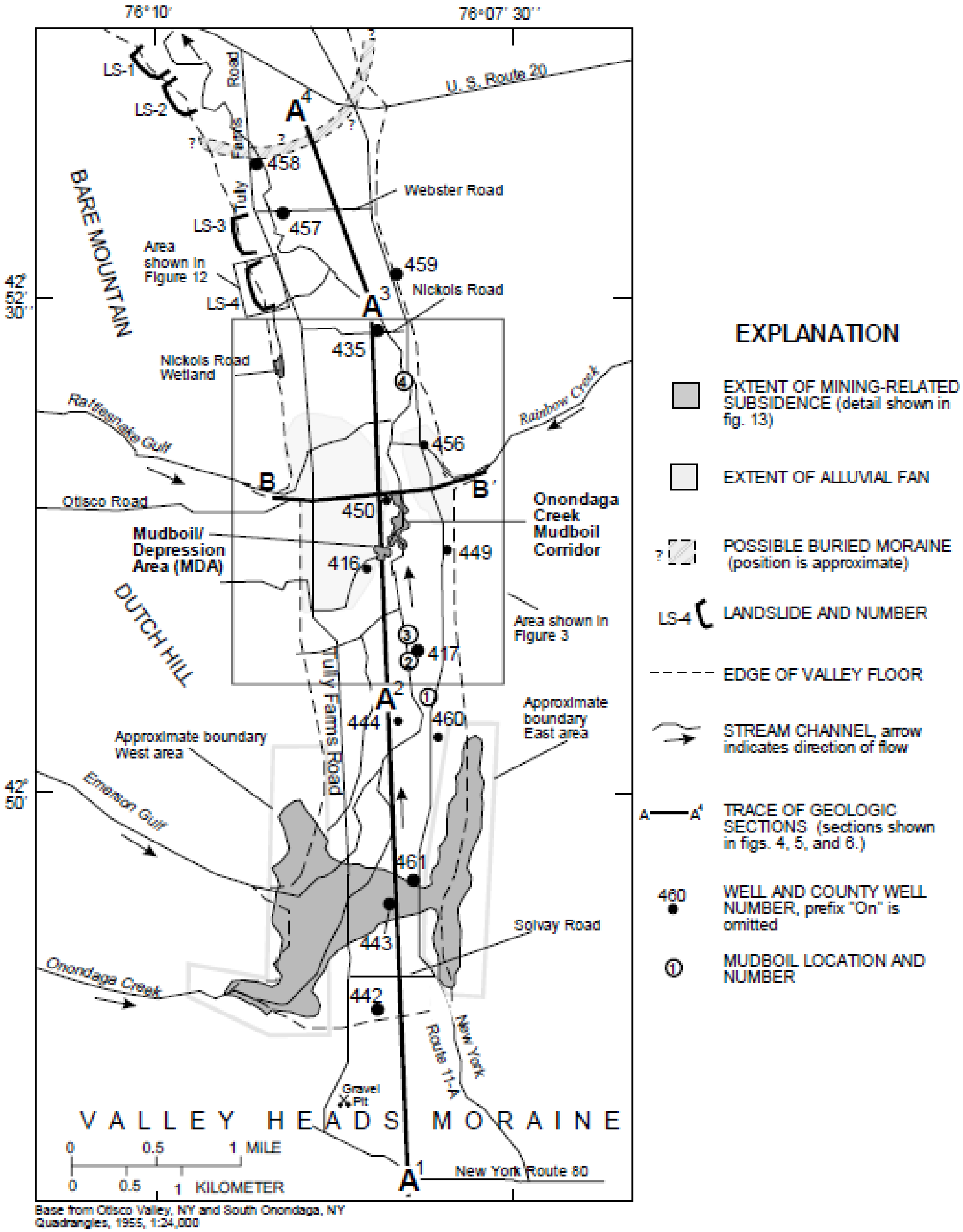


Figure 14. Principal geographic features of the Tully Valley (from Kappel et al., 1996).

Figure 15 is taken from an USGS Tully Valley longitudinal cross section (Kappel and Miller, 2005). Section E-E' passes approximately through the saline TVM zone and the solution mining areas lie approximately midway between Sections E and F. The figure demonstrates the prevalence of lacustrine silt and clay (lsc, beige color) in the valley, including the upper layer providing a semi-confining valley groundwater horizon. It also shows that a deeper ice contact sand and gravel zone (highlighted red outline, ic, orange) rises closer to grade in the mudboil area. Down valley from the mudboil area, near cross section D-D', there is also an increasing thickness of glacial till (t, pink). Cross section D-D' is situated just south of U.S. Route 20 (coincident with location A[4] on Figure 14). Note that the Tully Lakes lie immediately south of Section F-F' on Figure 15, from which water was initially diverted to provide high-head freshwater for solution brining.)

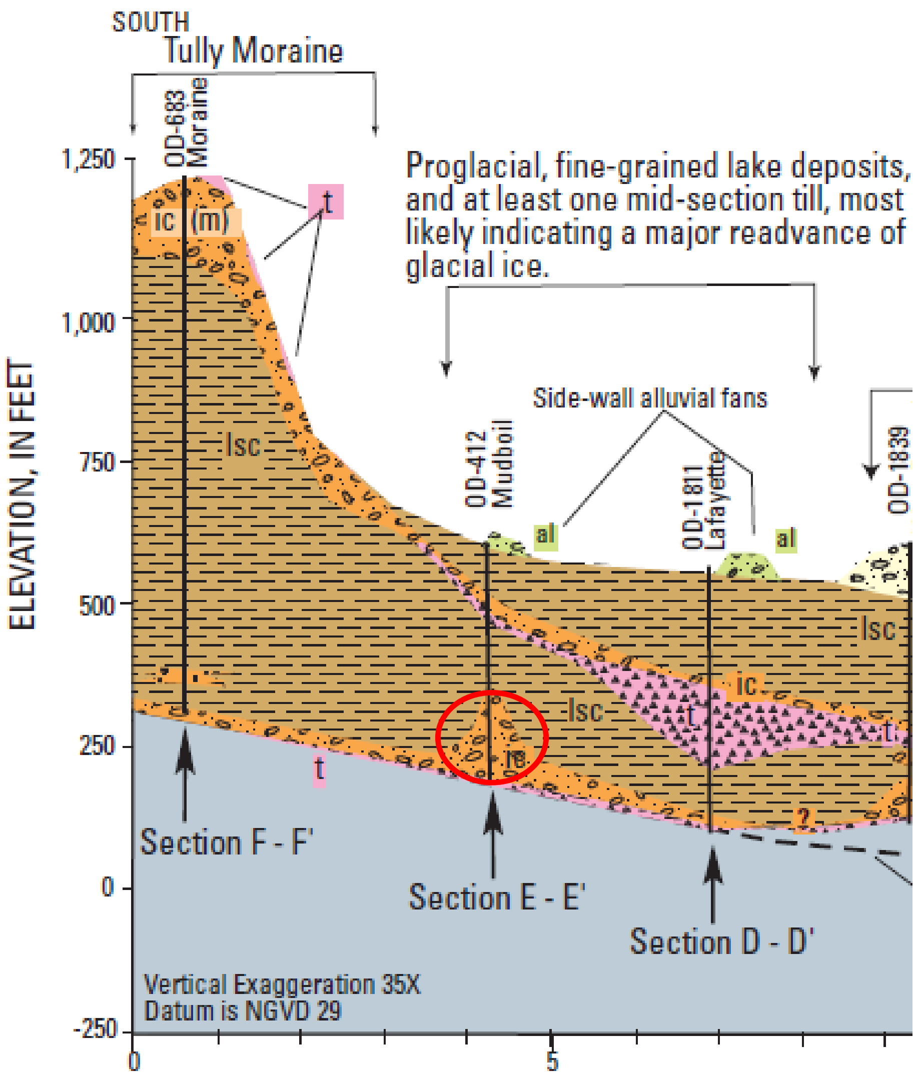


Figure 15. A longitudinal geological cross-section of the Tully Valley, showing Pleistocene deposits. Red circle highlights ice contact sand and gravel (ic) rising toward grade near mudboils. Source: Kappel & Miller, 2005.

The points on the previous pages collectively support an internally-consistent conceptual model explaining why saline mudboils appear north of the solution mining areas, namely:

1. The valley elevation drops to the north, lowering the land grade below the semi-confined potentiometric pressure surface in this area.
2. The salt rock formation rises to the north and the land surface falls to the north, together bringing salt closer to grade to the north. East-west rock lineaments may also allow some vertical brine flow pathways once solution channels extend under discrete lineaments.
3. The most permeable glacial sediments and some thinning of the semi-confining silts and clay appear under the mudboil area, providing brine migration routes of least resistance to the current saline TVM area.
4. Glacial till may inhibit further northward brine migration, limiting the northward migration of brine and forcing upward pressures under the full area between the solution mining area and the glacial till valley barrier.

5.4 Alternate Explanations

The lines of inquiry summarized above provide a clear and understandable history of mudboils in the Tully Valley. Other explanations have been explored over the past decades which, until the salt finger-print linked brine to saline TVMs, were worthy of consideration. Several of these are discussed briefly below:

<u>Alt. 1: Valley Heads Moraine, Rattlesnake Gulf and Rainbow Creek are pressure sources driving the Saline TVMs</u>. Some investigators have suggested the sources of artesian pressure driving mudboil activity came from the Valley Heads Moraine near Tully Lakes, or from the gravel fans around Rattlesnake Gulf or Rainbow Creek. These were reasonable potential sources of pressure, but can now be discounted for the following reasons:

1. Most importantly, none of these sources are saline. Early investigations of these locations mostly pre-dated recognition or arrival of salt impacts at the TVMs. However, now only sources of pressure which are also in close proximity to salt can now be considered.
2. Additional points further rule out Rattlesnake Gulf and Rainbow Creek as sources of pressure driving saline TVM activity:
    a. A USGS cross section (e.g., Figure 3 in Kappel, 2014) suggests vertical interconnections allow stream water from Rattlesnake Gulf to sink below the margins of the valley's semi-confined aquifer, pressurizing the mudboil area. The same mechanism has been suggested at the alluvial fan of Rainbow Creek to the east. However, the sediments mapped along the west valley wall appear to consist of "[l]aminated sand and silty clay," "[l]aminated sand and some silt/clay," and "[c]lay and silt." Along the east valley wall, the mapped sediments consist of "[l]aminated silty clay" and "[c]lay and silt". None of these materials are very permeable, making it unlikely that any significant volume of deep recharge enters semi-confined layers under either steam's alluvial fan.
    b. Mudboil emission rates reportedly vary in response to long seasonal cycles rather than to individual stormwater events. This suggests a more distant source of saline TVM recharge than the immediately adjoining stream alluvial fan sources.

c. The potentiometric pressure in the mudboil area rose to approximately 600 feet above sea level in the early 1990s (Kappel, 1992). This is above the elevation of the semi-confining silt and clay layer shown on Figure 3 of Kappel (2014) at the outlet of Rattlesnake Gulf and Rainbow Creek and essentially rules out both creeks. Neither is positioned at high enough elevations to generate the pressures observed at the saline TVMs.

3. The Tully Lakes, located on the high-elevation Valley Heads Moraine, have been presented by some investigators as sources of groundwater recharge to sediments under the valley bottom silts. But studies indicate that Tully Lakes have low permeability bottoms, consisting of "clay, silt, organic muck, marl, or perhaps, in places, dense till" that limit groundwater and surface water interaction. Gatehouse Pond is closest to the Tully Valley and its bottom is reportedly perched above the groundwater table (Kappel et al., 2001), suggestive of minimal leakage which might otherwise provide groundwater recharge in the direction of the saline TVMs. This is not surprising since most high elevation lakes that maintain stable water levels can only do so if their beds do not leak. Finally, it is worth noting that the lakes are all situated to the south of the Tully Valley watershed and naturally drain south via the West Branch Tioughnioga River. For all these reasons, it seems clear that the lakes exert no significant influence on groundwater pressures in the Tully Valley. Aside from the period when they were tapped to provide water to the early solution mining industry, they have also been essentially unchanged and no other lake management activities appear suited to explaining the periods of water pressure change noted in Tully Valley.

4. Some have suggested that Tully Valley confined pressures are recharged by the north-facing slopes of the Valley Heads Moraine. These are mapped as "ice-contact deposits consisting mostly of sand and gravel with some fine sand, silt, and till" (Kappel et al., 2001). The soils lie at the north margin of the Tully Valley watershed where they have undoubtedly always provided a measure of groundwater recharge to sediments in the Tully Valley. However, while mudboil pressures and composition have changed significantly over the past decades, little has changed on this landform aside from the initiation of a gravel mining operation for which the chronology of land clearing and mining does not align with the chronology of groundwater pressures noted in Tully Valley. We also note that while sand and gravel deposits are usually devoid of perennial streams since they allow high rates of aquifer infiltration, USGS topographic maps and USGS reports (Figures 1 and 5a/b in Kappel et al., 2001) show a series of perennial streams and springs on this north-facing slope (Figure 16) and the gravel mine itself is pock marked with ponds. Together, these suggest that infiltration rates are in fact quite poor on this hillside with any rapid infiltration promptly discharging to these perennial streams and springs and ponds. A possible explanation may be clay or silt horizons below the land surface.

   Chazen's best interpretation of these hydrogeologic conditions at the Valley Heads Moraine is that groundwater recharge from this area reasonably supports a measure of recharge to the Tully Valley's semi-confined overburden aquifer, but that the recharge rates have been both limited and essentially unchanged since glaciers left the valley and thus not responsible for the exacerbated saline TVM emissions of the past century.

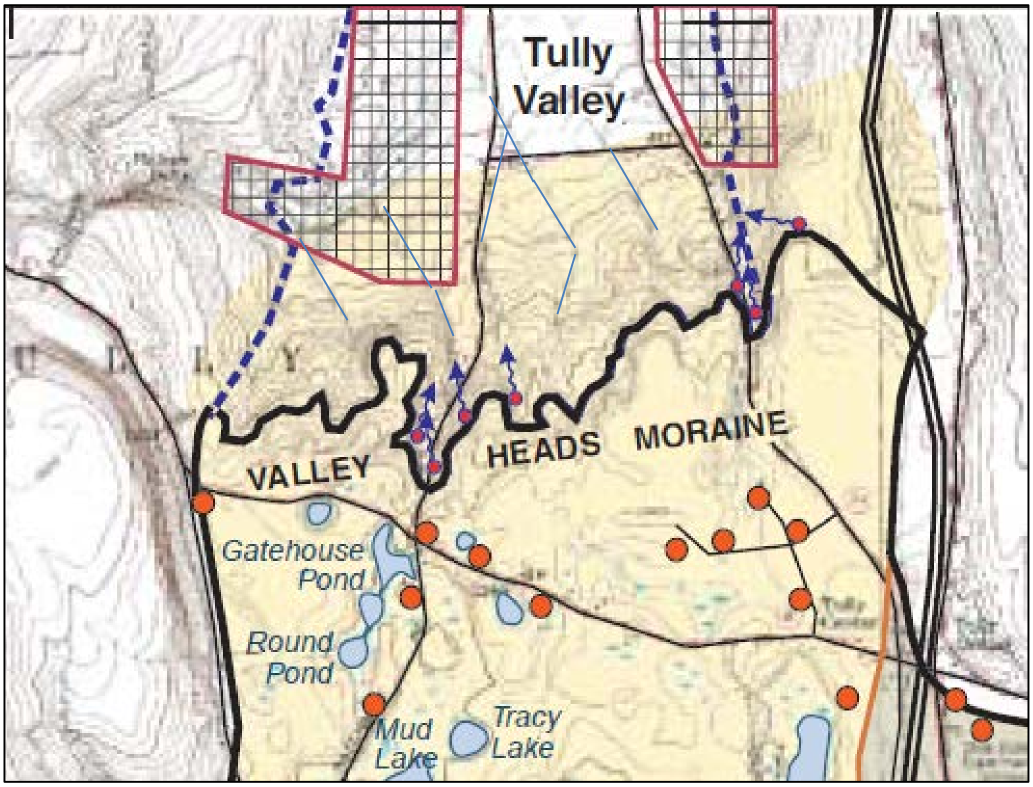


Figure 16. A map showing the location of springs (red dots) and highlighted perennial streams on the north-facing slope of the Valley Heads Moraine (from Kappel et al., 2001). Yellow shading identifies ice contact glacial sediments, the heavy black line marks the watershed divide and the former solution mining areas are gridded.

<u>Alt. 2: Pressures driving today's saline TVMs are relics of much greater post-glacial pressures up to 200 feet above the valley land surface; today's pressures are simply the final phases of pressure relief decaying over millennia throughout which time mudboils have always been active</u>. USGS explored this hypothesis as an adjunct inquiry while modeling brine sources nearer to Syracuse. The resulting groundwater-flow model of the Onondaga Valley glacial-drift aquifer by Yager et al. (2007) and Kappel and Yager (2008) suggested that when pressure relief assigned at mudboils and landslide spring discharges was removed from the USGS model, estimated artesian heads rose to 200 feet above the Tully Valley land surface. Kappel (2014) thus posited, "This excessive artesian pressure likely initiated mudboil activity following drainage of the last proglacial lake about 10,000 years ago."

Chazen's assessment is that this hypothesis does not withstand scrutiny for the following reasons:

1. USGS has also suggested (discussed previously) that recharge supporting saline TVMs might enter through Rattlesnake Gulf and Rainbow Creek alluvial fans, going so far as to show vertical flow pathways on Figure 3 of Kappel's 2014 report. It should be self-evident that alluvial fans cannot both provide seasonal recharge to a confined aquifer while simultaneously having failed to fully relieve 200 feet of extraneous pressure head. If there is any meaningful vertical flow at either creek's alluvial fans, 200 feet of vertical pressure could not have been confined for millennia.
2. The presence of 200 feet of pressure head above the valley floor for millennia would have driven historic mudboils far more active than today's emissions which relieve mere tens of feet of pressure. No field evidence suggests the deposition of millennia of silt tonnage in downstream sections of Onondaga Creek or Onondaga Lake, nor is there evidence of millennia

of cratering features visible around the current active mudboil areas. The oldest physically-observed and dated mudboil scars documented by USGS (Figure 12 in Kappel, 2014) appear only to date to the early 1900s.

3. The presence of millennia of presumably far more active historic mudboils, driven by significantly higher historic pressures, should have quickly relieved 200 feet of constrained pressure.
4. Finally, during a February 1, 2011, USEPA mudboil webinar, the Question and Answer transcript includes a comment by USGS geologist William Kappel providing some clarification of the level of confidence which should be placed on this matter:

   "The model that (Dick [Yager]) created was specifically designed for the brine field part of the aquifer [nearer to Syracuse], generally from the Onondaga Nation north. We had some data to the south that (Dick) was able to use, very sparse data. I would not feel comfortable with the model as it is right now in doing scenario testing in the Tully Valley."
   (Attachment 9 in USEPA, 2011).

Considered collectively, USGS' brief exploration of a model scenario not calibrated for the upper Tully Valley, generating output inconsistent with the lack of supporting field evidence of severe historic mudboil scars, and ignoring that millennia of very-active historic mudboils should have bled off suggested pressures, all severely discount the merits of this briefly considered model.

<u>Alt. 3: Paleoslides and buried wood suggest mudboils may date back millennia</u>. Investigations after the 1993 landslide identified the presence of various older landslides (paleoslides) in the valley. USGS reports that the Webster Road landslide (LS-3 on Figure 14) is approximately 7,000 years old and others are between 4,700 and 11,000 years old (Kappel, 2014). Thus, it appears to Chazen that landslides in the Tully Valley study area are either many millennia old, or occurred in the past 25 years. Given the timing and the presence of swarms of saline springs noted around the 1993 landslide, the recent slide is expected to have been influenced not only by seasonal precipitation, but also by the recent sharp increases in potentiometric pressure associated with cessation of formal brine mining. Similarly, saline TVM emissions and impacts to a nearby wetland peaked following sealing of the east and west brinefields. The much older, historic landslides are more reasonably attributed to land surface response to rebound (isostatic rebound) occurring primarily during the immediate post-glacial period along with associated paleoclimate weather transitions and area-wide revegetation patterns. Discussion of the 1993 landslide is not the central subject of inquiry for this paper and so is only evaluated here due to the potential association Chazen has noted between the saline TVMs, a wetland studied by USGS, and the 1993 landslide.

USGS in 2014 also references otherwise apparently unpublished age-dated woody debris found in Onondaga Creek sediments (Kappel, 2014). The text indicates that wood fragments 350 to 500 years old were found buried in shallow alluvial floodplain sediments and that walnut and sycamore wood dated 950 and 1,350 years old, respectively, were found buried in underlying gravel. Finally, a 6,800-year-old tree stump was identified in the exposed Onondaga Creek channel. The 2014 paper offers a scenario based on these matters as follows:

> *"These carbon-14 dates, along with the coarse gravel material present at depth in the corridor and not the surficial red clay that is found upstream and downstream from the mudboil corridor in Onondaga Creek, are indicative of long-term mudboil activity and land-surface subsidence in the corridor long before human activities could have affected the mudboil activity."* (Kappel, 2014).

Chazen questions, given the dynamic nature of erosion and deposition of active streams, why old wood buried under recent alluvial clay, gravel, or even mobilized mudboil sediments somehow proves that mudboils have persisted for millennia. Various investigators have noted that it is extremely difficult to distinguish between Tully Valley mudboil sediments and other stream corridor alluvium since both are derived from silty-sand glacial era deposits. Therefore, unless further analysis demonstrates that the sediments enclosing the wood have remained undisturbed since placement and match the age of the wood, we believe no such conclusions can be drawn about when these old woody materials were positioned at their current locations. Further dialogue with USGS might help clarify this matter, but unless and until clarified, Chazen believes the 2014 statement is tenuous at best, particularly when evaluated in light of the many other lines of reasoning speaking exclusively to saline TVM activity limited to the past century.

<u>Alt. 4: A lower brine aquifer is the source of salinity in the saline TVMs</u>. USGS refers to the Tully Valley confined glacial aquifer as having an upper (fresher) and deeper (brackish) zone (Kappel, 2014). The inference is that the brackish zone is the source of TVM salinity. The text however offers no explanation as to how or when the deeper zone became brackish.

Chazen suggests all sediment aquifer horizons in the upper Tully Valley were historically freshwater. The lower zone of the glacial aquifer became brackish first as brine lost from the pressurized deep halite bedrock mining activity seeped upward. Such upward migration of brine would first have seeped through any porous bedrock horizons under the valley. This would include the Rondout formation situated above the halite formation, which Mr. Mike Slezak the Brine Wellfield Superintendent from 1967-1978, recognized as a 20 foot “loss zone” containing brackish water (Slezak, 2014).

Once migrating upward through the more than 1,000 feet of overlying shale and limestone, the lost brine then would have penetrated the sedimentary aquifer sediments, lower horizons first, before eventually breaching to grade. In this sense, the lower brine aquifer would indeed be the source of salinity in the saline TVMs, but only with the added recognition that deep solution mining was the original source of salinity in the brackish, lower sediment aquifer.

Anecdotal evidence indicates that the solution mining industry paid to replace local resident’s wells with a public water supply as private wells became increasingly brackish over time. The timing and rationale for this industry commitment is unknown to Chazen since records associated with this matter are reportedly sealed under confidentiality agreements with the landowners receiving public water. However, the implication is that the mining industry recognized at some point that increasingly brackish groundwater was seeping into domestic well aquifer horizons and paid for installation of a public water supply.

<u>Alt. 5: Geochemistry suggests other source formations</u>. Various investigators over time have suggested that the TVMs are not related to brine mining activities because of differing geochemical fingerprints at the times of sampling. However, as time has passed, the geochemical signatures of the mudboil flows and the deep halite deposit waters have increasingly converged. Specifically, where the TVMs were formerly freshwater, they now contain anion and cation signatures consistent with those of the Syracuse halite formation (Baldauf, 2003).

The passage of time has erased most reasonable questions about whether the salt signatures are different. The convergence of water quality between the deep solution mining brine and mudboil discharges are now consistent with Chazen’s overall conceptual model of an advancing solute wavefront reflecting the spread of lost brine from solution mining areas into areas of prior freshwater aquifers and the Onondaga Creek.

Alt. 6: Mudboils may be both natural and human-influenced. One USGS researcher has consistently repeated this proposal. For example:

> *"These [Tully Valley] phenomena include mud volcanoes or mudboils, landslides, and land-surface subsidence; all are considered to be naturally occurring but may also have been influenced by human activity."* (Kappel, 2014)

It is Chazen's view that such uncertainty may have been justified when studies in the Tully Valley were first initiated some twenty to thirty years ago. However, the now well-developed record of geochemistry, physical phenomenon, tree ring history, and evaluations of the solution mining methods used in the Tully Valley all converge to provide a preponderance of evidence linking these phenomena to brine mining activities. Interestingly, where Mr. Kappel is the second author rather than the primary author, USGS publications more firmly associate solution mining with brine and pressure dissemination throughout Tully Valley. See, for example, Yanosky's firm association of solution mining impacts on wetland vegetation (Yanosky & Kappel, 1998).

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In summary, Chazen acknowledges the merit of the multiple lines of inquiry reviewed above in this Section, but believes a reasonable interpretation of the preponderance of data now available from the Tully Valley indicates mudboils first appeared near Onondaga Creek in the late 19th century and all significant associated impacts are attributable to the valley's solution mining history. Mudboils indisputably become more active as wild brining practices expanded and subsequently when brine wells were sealed and no longer relieved the valley of 1 billion gallons of brine annually. There is no oral or written history supporting the existence of pre-mining mudboils, and no field evidence that Chazen has reviewed suggests that saline mudboils were present prior to solution mining activities. The simplest and least contradictory explanation for saline mudboil emissions, correlated by chemistry, pressure, and geography, links saline TVMs to the history of solution mining in the Tully Valley and recognizing this relationship provides keys to mudboil remediation.

6. REMEDIAL RECOMMENDATIONS

Mitigating the Tully Valley saline mudboils is a challenge that should address both short-term and long-term solutions to be effective. Chazen recommends below remedial strategies to reduce imbalanced valley potentiometric pressures which not only drive saline TVMs but are also impacting wetlands and land stability.

Beyond sealing unused brine wells, mitigation efforts have to date focused on reducing the impacts of specific mudboil silt flows entering Onondaga Creek. Uncontrolled silt discharges have resumed when these efforts ended. No efforts have yet been attempted to manage salinity. If only such "end of pipe" mudboil controls continue to be considered, the volumes of silt and salinity concentrations requiring control can be expected to increase as uncontrolled wild-brining continues.

The kinds of physical mudboil management systems previously attempted could certainly be maintained by new engineered systems, including expanded engineered dikes or berms and depositional basins around mudboils to trap sediments. But methods to manage salinity are also needed, involving collection of saline waters and treatment to reduce salt to help protect the geochemical and physical quality of the Onondaga Creek and the surrounding wetlands. A water treatment facility at the flood control dam downvalley from the saline TVMs could therefore be considered, although it would need a perpetual budget for periodic monitoring, ongoing treatment, adjustment, relocation, replacement, and repair to remain effective.

Meanwhile, the driving forces generating the saline TVMs would persist. So while short-term mitigation efforts as those attempted thus far should be applauded, they must be viewed only as stop-gap measures while more holistic effective long-term solutions are being evaluated, funded, and implemented.

Chazen recommends instead considering long-term mitigation which focuses on permanently repairing the local hydrogeologic regime. Otherwise wild brining will continue and expand cavern formation in the subsurface. As long as surface water easily enters and leaves ever-expanding salt chambers, rock salt underlying Tully Valley will continue to dissolve. Cap rock over ever-expanding salt caverns will thus continue to either settle or collapse, more sinkholes and hillside fissures will form, and ongoing saline TMVs, damaged wetlands, and elevated soil pore pressures will persist.

Development of a long-term remedial action plan should consider each of the elements below, separated into three general categories:

<u>Intercept freshwater before it becomes brine</u>:

- Implement measures to prevent surface runoff from entering hillside fissures.
- Divert surface water and runoff from sinkholes.
- Explore measures to reduce pressure head in deep sediments near and upgradient/upvalley of the former solution mining areas so that the pressures driving the mudboils are reduced. Compensatory fresh groundwater extraction may be part of this remedial tactic.

<u>Seal off the caverns and solution channels in the halite rock horizons where brine is generated</u>:

- Implement measures to stop wild brining by sealing off damaged solution caverns in the rock salt and associated collapse chimneys so that shallow freshwater no longer generates brine.

Slow brine flow between points of generation and saline TVMs:

- Use grouting or other measures to slow brine migration between the cavern depths and the discharge points at saline mudboils.

To address each of these lines of inquiry, Chazen has developed a comprehensive framework of specific approaches. Each is highlighted on Figure 17 below and discussed in further conceptual detail.

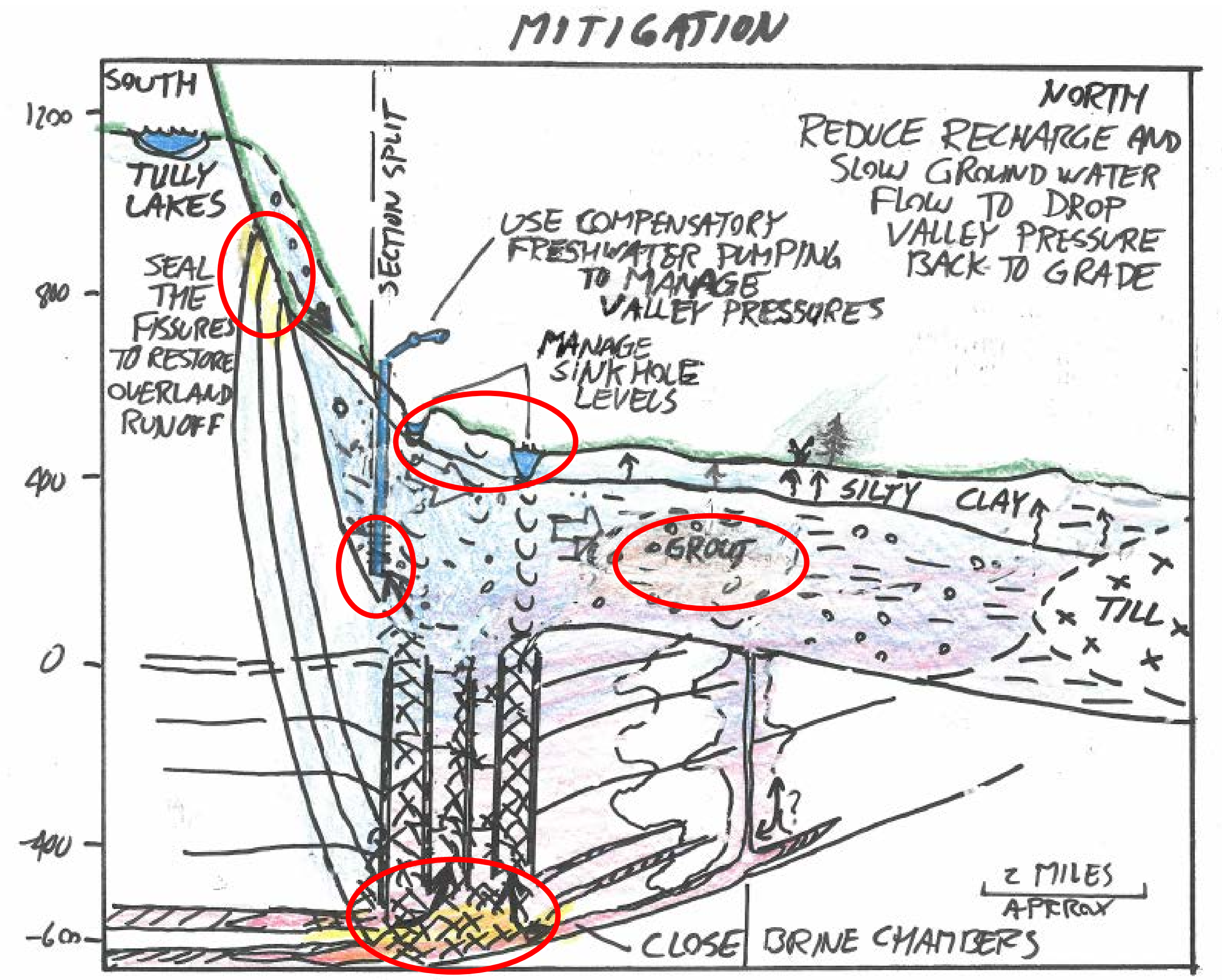

Figure 17. Potential means of remediation of saline groundwater flows in the Tully Valley. Figure prepared by Chazen.

Recommended remedial strategies:

- Slow rates of fresh water entry. Reduce sources of freshwater entry surcharging the valley's geologic formations, generating both unwanted pressures and lost brine. Measures recommended to control this recharge cycle include:
  - o Bridge or seal the hillside fissures. This will prevent overland flow from surcharging subsurface geology. It will also restore overland flow volumes going directly to Onondaga Creek. A bentonite/cement slurry or equivalent should be considered to seal

the fissures. The material used must be flexible enough to adapt to and continue sealing fissures in spite of inevitable future movement of these hillside joints. Sheet wash and surface drainage along the flanks of the valley may in some instances also be diverted around existing fissures. Fissure mitigation may be prioritized based on estimated volumes of overland flow entering individual fissures (e.g., first priority for fissures in steam beds or near the bottoms of individual sub-drainages and fissures perpendicular to extensive hillside areas, etc.).

- o Drain and divert runoff around remaining uncontrolled sinkholes. In subsidence and sinkhole areas, grading work should continue to prevent flows of surface water to any sinkholes. Efforts already in place limit water level peaking in existing sinkholes. This should be expanded to all sinkholes, preventing even temporary peaks in sink-hole standing water levels relative to surrounding shallow groundwater elevations.

Recognizing that sealing fissure and diverting sinkhole flows will be challenging and require considerable time, compensatory withdrawal of fresh groundwater is also recommended as an interim pressure mitigation strategy. With a permit, freshwater can be pumped from deep sand and gravel horizons near the solution mining areas into Onondaga Creek. This will both reduce valley groundwater pressures and, as a secondary benefit, will augment Onondaga Creek flow with fresh water able to dilute current creek turbidity and salinity.

Groundwater should only be withdrawn from areas upgradient or cross-gradient from the closed solution mining fields where it will both lower valley groundwater pressures and intercept fresh groundwater that might otherwise reach salt caverns and become new brine. Figure 17 shows this concept.

The USGS explored installation of pressure relief wells near the mudboil area. The effort was only focused on conveying salty groundwater past the semi-confining silt-clay horizons in order to limit silt transport into the creek and slow radial land cratering (Kappel, 2014). The wells failed in part because they were not installed in sufficiently coarse sediments to avoid plugging over time. More importantly, the extraction of salty water from pressure relief wells did not fundamentally differ from industrial will brining since, in some manner, the action just re-activated saline water removal. Thus, while pressure relief wells installed near the current mudboils may be considered a worthwhile experiment, the inquiry should not be expanded here. Instead, freshwater compensatory pumping at far higher rates is recommended further up Tully Valley where only freshwater would be extracted which might otherwise seep down into halite caverns to form brine.

- <u>Evaluate options to seal off and fill the solution caverns and channels in the halite formation</u>. Investigation of suitable sources of inert, stabilized fill is recommended. Filling the cavities would likely occur over many years and require a degree of mechanical mixing and injection near the former brine field areas. The work would also involve filling not only open caverns, but void spaces filled with collapsed rock rubble in overlying collapsed rock chimneys. As of 1992, between 17,000 and 22,000 acre feet of void space was estimated to remain underground (CS Consulting Engineers and H&A of NY, 1992). This void volume has in all probability increased since 1992 since wild brining continues daily. In addition, the original estimate may have overlooked an equivalent volume of void space associated with the dissolution of lost brine. Filling caverns and voids in the bedrock formations under Tully Valley represents the only permanent solution to geotechnical stabilization of the valley, the restoration of halite isolation, and thus the mitigation by complete flow interruption of hazards associated with ongoing brine generation. The use of the Valley's sub-grade void space may also represent a business opportunity for materials potentially suitable for permanent isolation including such clean by-products as quarry fines or equivalent materials.

- <u>As the flow cycle is slowed by cavern filling and fissure/sinkhole management, restriction of uncontrolled brine migration between halite horizons and Tully Valley may be explored.</u> Brine migrating up toward grade is expected to follow preferential pathways through the most damaged rock and then through the most permeable overburden sediments. Existing flow routes in overburden sediments may be identified using, for example, boring tools equipped with conductivity (proxy for salt) sensors. Grout slurry pumped into these preferential pathways will beneficially slow current rates of brine migration toward the saline TVMs. Impeding brine migration must however only be performed in conjunction with controlling entry rates of source water entry and/or deep cavern filling so flow path grouting does not simply displace saline TVMs to new locations.

The various measures recommended above will together slow the cycle of freshwater movement through the damaged deep rock environment and reduce volumes of uncontrolled brine generation and export. The recommended approaches will: (1) reduce freshwater recharge and groundwater pressure by sealing routes of entry at sinkholes and hillside fissures and by active compensatory fresh water removal from the shallow aquifer near the former solution mining areas, (2) seal the salt caverns where freshwater has continued to encounter halite and become brine, and (3) lower the permeability of preferential pathways currently allowing brine movement toward the saline TVMs. These efforts are sharply different from "end of pipe" solutions, such as mudboil containment, ecological adaptation approaches, near-stream relief wells, or sediment and salt filtering. The recommended approaches also offer resolution not only to saline TVMs but also to other saline spring discharges, wetland damage, and landslide hazard.

7. CONCLUSIONS

The true challenge facing those charged with care of the Tully Valley is not simply to contain and treat saline TVMs, but more centrally to recognize and then seek to reduce or eliminate the effects of continuing wild brining which include saline TVMs. This ongoing action drives the TVMs as well as other hazards. Begun as an intentional, industrial wild-brining activity, the human-initiated wild brining practice will not have been effectively discontinued until the pathways for recharge to the salt formations are identified and reduced or eliminated. Locating and plugging all of the hillside fissures and filling voids created in the salt may seem impractical and expensive, but the task is possible with available technologies. Grouting along the brine plume flow path is also a highly feasible technology. And a business model may exist for sealing/filling the deep salt caverns and overlying bedrock voids. Consideration should be given to each of these long-term, permanent mitigation approaches.

We believe this analysis has fully synthesized all data from prior reports into a single Tully Valley hydrogeologic presentation. It draws together, for example, tree ring data, geochemistry studies, the many studies conducted near mudboil areas, and available industry mining records. This synthesis has helped Chazen focus on and point to remedial options most likely to permanently and effectively manage not only saline TVMs but also to mitigate ongoing harm to wetlands and hazards to property.

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