Hydrogeology of The Tully Valley and Characterization of Mudboil Activity, Onondaga County, New York

By William M. Kappel, Donald A. Sherwood, and William H. Johnston

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CONTENTS

Figures

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To Obtain
	Length	
inch (in)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Slope	
ft/mi	0.1894	meter/kilometer
	Area	
square mile (mi^2)	2.590	square kilometer
acre	0.40483	hectare
	Flow	
cubic foot per second (f.^{3}/s)	0.02832	cubic meter per second
inch per year (in/yr)	25.4	millimeter per year
million gallons per day (Mgal/d)	3.785	cubic meters per day
gallons per minute (gal/min)	0.06309	liter per second
gallons per second (gal/s)	0.001052	liter per second
	Volume	
cubic feet (ft^3)	0.02832	cubic meter
cubic yards (yd^3)	0.7646	cubic meter
acre feet	1,234.	cubic meter
billion gallons (Bgal)	3.785×10^6	cubic meter
	Temperature	
degrees Fahrenheit (°F)	°C = 5/9 (°F-32)	degrees Celsius

Specific Conductance

microsiemens per centimeter at 25° Celsius (µs/cm)

Equivalent Concentration Terms

milligrams per liter (mg/L) = parts per million
micrograms per liter (ug/L) = parts per billion

Multiply	By	To Obtain
	Load	
tons per day (ton/d)	0.9072	megagrams per day
	Pressure	
pounds per square inch (lb/in.^{2})	0.07031	kilograms per square centimeter

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Water Year: In this report "water year" is the 12-month period from October 1 through September 30. The water year is desginated by the calendar year in which it ends and includes 9 of the 12 months. Thus, the year ending Sepember 30, 1995 is called the "1995 water year."

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Abstract

Mudboil activity in the Tully Valley, in central New York, is causing turbidity in nearby Onondaga Creek, where it has caused a bridge to collapse; it also has threatened or damaged other structures and has caused extensive land subsidence. Mudboil activity was intermittent from its first reported appearance in the 1890's until the 1970's, when the rates of mudboil discharge and land subsidence began to increase. Historically, the water discharged from mudboils was reported as fresh, but chemical analyses in the late 1970's indicated an increase in specific conductance and chloride concentration.

Mudboil discharge is driven by artesian pressure in unconsolidated sediments that are confined by a 60-foot layer of silt and red clay. This process, once begun, has been self-propagating. Artesian pressures are about 20 feet above land surface over most of the valley floor but exceed 30 feet above land surface along Onondaga Creek where Rattlesnake Gulf and Rainbow Creek enter the Tully Valley. The source of artesian pressure is recharge from the Tully (Valley Heads) Moraine at the south end of the valley, and the alluvial fans of Rattlesnake Gulf and Rainbow Creek. The mudboils are found within a 300-foot-wide by 1,500-foot-long corridor along Onondaga Creek just upstream from the two alluvial fans, and in a 5-acre subsided area just west of that corridor.

Remediation efforts have entailed (1) diversion of flow from the tributary that feeds the subsided area, (2) installation of depressurizing wells at several locations, and (3) construction of a dam and settling impoundment to detain mudboil sediment that would normally discharge to Onondaga Creek. These efforts have been partly successful, but further work is needed to slow the mudboil activity, which is expected to persist in both areas. Mudboil activity is normally greatest during the early spring and late fall, when artesian pressures increase in response to seasonal ground-water recharge.

Suspended-sediment concentrations at the outflow of the subsidence area ranged from 31,210 mg/L (milligrams per liter) in October 1991 to 17 mg/L after remediation efforts in the summer of 1993. Yearly average suspended-sediment loads to Onondaga Creek from the subsidence area for water years 1992, 1993, 1994, and 1995 were 29.8, 9.75, 1.41, and 1.80 tons per day, respectively. Sediment discharged from the mudboils initially was 30 to 60 percent clay and 80 to 100 percent silt-sized or smaller sediment, and the sand fraction never exceeded 20 percent. After the remediation projects, 50 to 80 percent was clay, and nearly all sediment was silt size or smaller.

Analyses of water from upstream and downstream of the subsidence area, as well as from mudboil vents within that area, indicate that the source of water for some mudboils is a confined freshwater aquifer, whereas for others it is an underlying, brackish-water aquifer. Water from the freshwater aquifer has specific conductance values ranging from about 400 µS/cm (microsiemens per centimeter at 25° Celsius) to almost 900 µS/cm, dissolved chloride concentrations range from 37 to 430 mg/L, and dissolved-solids concentrations range from 215 to 463 mg/L. Specific conductance of water from the brackish-water aquifer ranges from 17,000 to 28,000 µS/cm, chloride concentrations range from 2,000 to 7,100 mg/L, and dissolved-solids concentrations range from 4,200 to 12,800 mg/L.

The largest landslide in New York State in the last 75 years occurred at the foot of Bare Mountain, 1 mile downstream from the mudboil area, in April 1993 and was the fourth in a series of slides that have occurred at the base of this hill. Slope instability was reported as early as May 1990. After the slide, intermittent mudboil-like activity was observed at several springs within the backscarp of the slide; water from these springs ranged from fresh to brackish. The chemical similarity between water from some springs in the backscarp area and water

in the lower (brackish) aquifer beneath the mudboil area may indicate a hydraulic connection between this aquifer and the surficial deposits.

Hydrologic changes in the valley during the last 100 years have been attributed to salt-solution mining in the upstream (southern) end of the valley. The removal of nearly 150 feet of salt from four evaporite beds in the Syracuse Shale of the Salina Group has caused the collapse of bedrock and unconsolidated deposits in and near the brine field, 3 miles south of the mudboil area. These collapses have created a hydraulic connection among bedding plane aquifers in the bedrock and increased the hydraulic connection with unconsolidated aquifers. The ground-water flow system after brine field closure in 1988 may have reached a new semiequilibrium, but mudboil activity will likely continue because artesian pressures remain. Whether mudboils were present before salt solution-mining began is unknown.

INTRODUCTION

The Tully Valley, which lies about 15 mi south of Syracuse, N.Y. (fig. 1), contains an unusual area in which turbid water carrying fine-grained sediment is continuously discharged at land surface from volcanolike features known as "mudboils." This discharge flows to, and causes turbidity in, nearby Onondaga Creek, a tributary to Onondaga Lake, 15 mi. downstream. The continuous discharge of sediment through mudboils also has caused land to subside more than 15 ft. Mudboil activity also has destroyed two road bridges, severed a buried telephone cable, and necessitated the rerouting of a petroleum pipeline. The persistence of mudboil activity is of concern to local homeowners as well as to county and State governmental agencies.

In 1991, the U.S. Geological Survey (USGS), in cooperation with the Onondaga Lake Management Conference (OLMC) and the U.S. Environmental Protection Agency, began a 4-year study to:

(1) identify the extent and mechanism of mudboil development in the Tully Valley;

(2) conduct an extensive test-well drilling program to identify and document the glacial stratigraphy and aquifer conditions in the valley in and near the active mudboil area, including a deep test well that penetrated the salt beds below the mudboil area;

(3) summarize results of the 4-year streamflow- and sediment-monitoring program at the mudboils to determine the amount of water and sediment discharged to Onondaga Creek and to identify what remedial action could be taken to reduce that discharge; and

(4) develop theories as to what may have caused mudboils to appear.

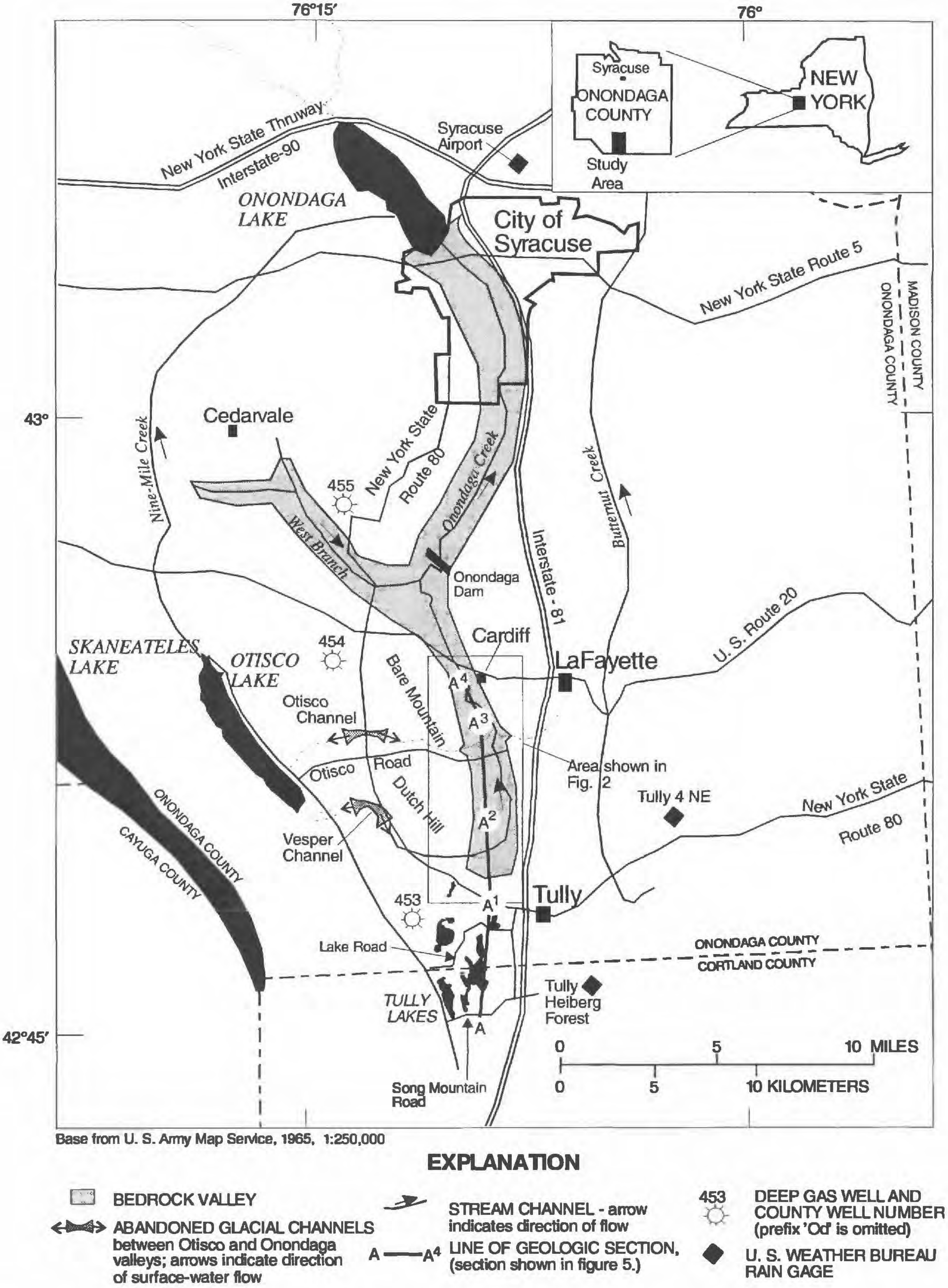
This project has been funded wholly or in part by the United States Environmental Protection Agency under Interagency Agreement DW14941626-01 to the U.S. Geological Survey. The contents of this document do not necessarily reflect the views and policies of the Environmental Protection Agency .

Study Area

The Tully Valley is a glacially scoured river valley about 7 mi long and 1 mi wide that extends south to north from the northern escarpment of the Appalachian Uplands toward the Lake Ontario Lowlands. The valley contains the southern branch of Onondaga Creek, which flows northward to Onondaga Lake (fig. 1), which in turn flows to Lake Ontario. The bedrock valley contains 400 ft of unconsolidated sediment that was deposited during several periods of Pleistocene glaciation (Megan Hodgins, Hartwick College, written commun., 1994). The extensive bedrock scouring, followed by several periods of glacial-lake impoundment and their eventual draining, has left a nearly flat-floored valley that has been referred to as the "dry Finger Lake" (Mullins and others, 1991).

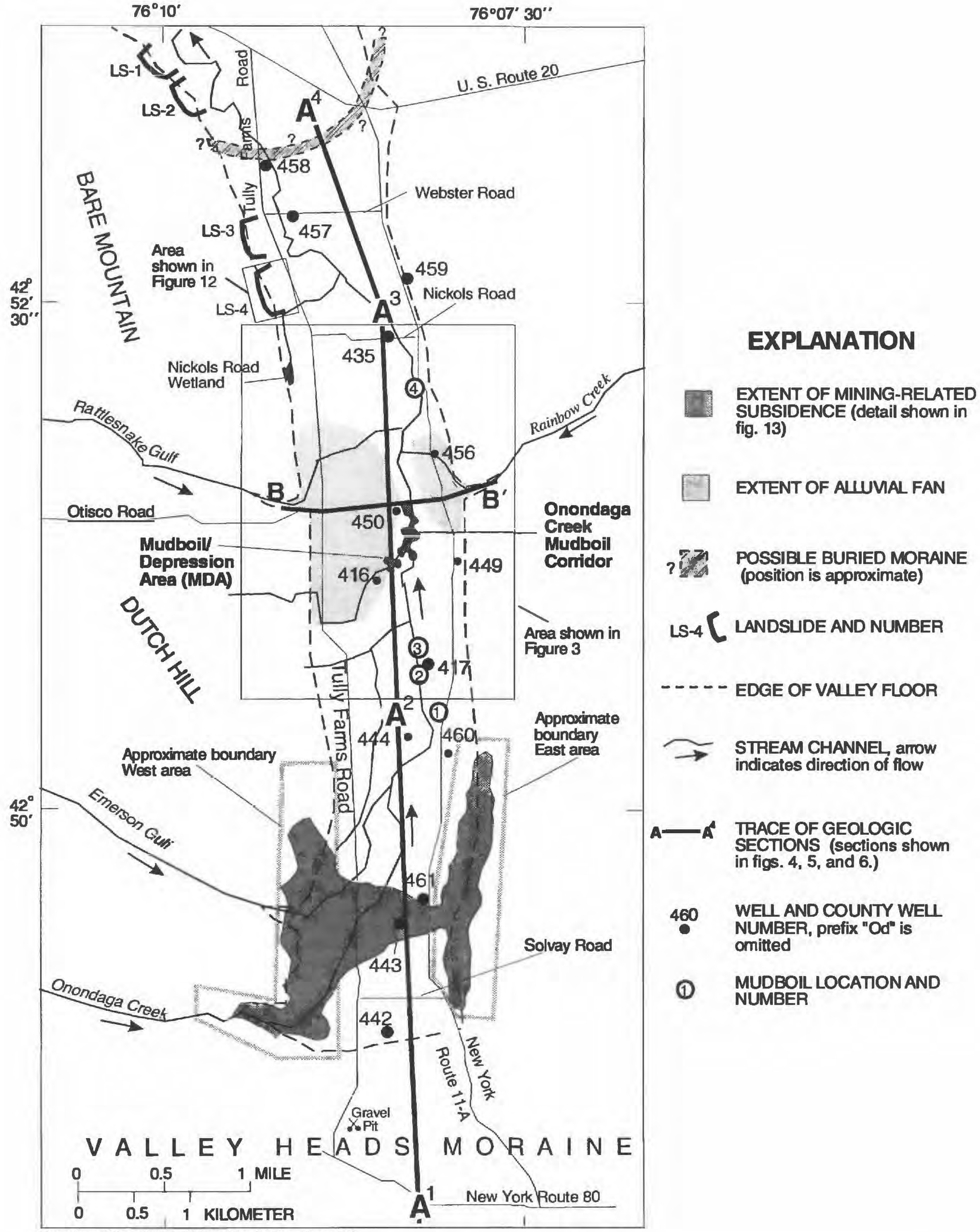
The valley walls are forested and steep and are generally mantled with a thin layer of soil overlying shale bedrock. The valley floor is extensively farmed and is underlain by fine-grained lacustrine sediments. The upstream (south) end of the valley is covered by coarser sediments that form the head of the Tully (Valley Heads) Moraine. Alluvial fans emanate from the tributary valleys of Rainbow Creek and Rattlesnake Gulf, halfway up the valley and just north of Otisco Road (fig. 2).

Salt-solution-mining areas flank the east and west valley walls at the south end of the Tully Valley (fig. 2). The east area was developed in 1889 after the discovery of a 45-ft layer of salt 1,216 ft below land surface (Larkin, 1950); production continued there through the late 1950's. The west area was



Base from U. S. Army Map Service, 1965, 1:250,000

Figure 1. Location and pertinent geographic features of Tully Valley, in southern Onondaga County, N.Y. and location of geologic section A-A^4 (Geologic section shown along A-A^4 in fig. 5.)



Base from Otisco Valley, NY and South Onondaga, NY Quadrangles, 1955, 1:24,000

Figure 2. Principal geographic features of Tully Valley, N.Y. and locations of wells, brinefield areas, landslides, mudboils, and geologic sections A^1-A^4 and B-B′. (Geologic sections are shown in figs. 4, 5, 6, and 7.)

developed in 1895 and remained in production through the late 1980's. The solution-mining operation entailed drilling wells into the salt beds and injecting freshwater from the Tully Lakes, south of the Tully Moraine (fig. 2), to dissolve the salt and produce a saturated brine. These lakes are 500 ft higher than the brine wellheads, and the elevation difference was sufficient to lift the dense, saturated brine from the wells. The brine was then discharged to a pipeline and flowed north to Syracuse, where it was used in the production of soda ash. At peak production, about 1 Bgal of brine per year was piped to Syracuse. In 1986 the west brine field ceased most operations, and a few wells were sold to another manufacturer, who ceased all brining operations 2 years later.

Mudboils have been observed in the Tully Valley for nearly 100 years (appendix 1). Most of the mudboils are in two areas–the Onondaga Creek mudboil "corridor," which is 1,500 ft long and 300 ft wide along Onondaga Creek, south of Otisco Road (fig. 2), and the 5-acre area of subsidence, locally known as the mudboil/depression area (MDA), just west of the southern (upstream) end of the mudboil corridor. The MDA contains most of the active mudboils and contributes most of the sediment that is discharged to Onondaga Creek from this part of the valley; it also has the greatest amount of mudboil-induced land subsidence in the valley.

Purpose and Scope

This report (1) documents the hydrogeology of unconsolidated deposits and bedrock in the Tully Valley; (2) describes the extent and effect of salt removal in the south end of the valley; (3) discusses the origin and persistence of mudboil activity and land subsidence in the valley, and (4) discusses the remedial efforts undertaken during the 1992-95 study and their effectiveness. It also presents (a) hydrographs of inflow to, and outflow from, the MDA as well as a synthesized hydrograph of MDA mudboil discharge; (b) data from selected wells, including a deep test well that penetrated the salt beds below the mudboil area; (c) sediment concentrations and load discharged from the MDA to Onondaga Creek during water years 1992-95; and (d) geologic sections showing the stratigraphy of unconsolidated deposits in the mudboil area. Appendix 1 presents a historic chronology of mudboil activity, the salt solution-mining operations, and other pertinent information from 1800 to the present, and appendix 2 presents water-quality data collected from the deep test-well program and from mudboils and springs in and around the mudboil study area.

Previous Studies of Mudboils

Mudboils, as described in the geologic literature, are generally associated with short-term increases in hydraulic pressure below a confining layer of sediment. During an earthquake, for example, seismic activity can liquefy fine-grained, saturated sediments, and if these sediments are forced upward through fractures in an overlying confining layer, they can form mudboils or sand boils. For example:

(1) Wills and Manson (1990) describe sand boils that erupted in Soda Lake, Calif., along fissures and scarps in the lake bed after it fell 4 ft in response to the Loma Prieta earthquake of April 18, 1990. Grain-size analysis indicated that the discharged material was a well-sorted sandy silt. The reason the sediments became liquefied was that they were of uniform grain size, were fully saturated, lacked a cohesive clay matrix, and were uncompacted before the earthquake.

(2) Waller (1966) reported that, during the Alaska earthquake of March 1964, water and sediment ejections occurred as far as 250 mi from the epicenter of the earthquake. Ejections were associated with linear fractures or points of weakness within a confining layer. Most of the ejected materials were fine-grained sediments, but gravel and sand were discharged at some sites.

Mudboil-like features also have been related to freeze-thaw conditions; for example:

(1) Dionne (1973, 1975) noted that silt, clay, and fine sand are pushed upward through partly frozen surface sediments in northern Quebec tidal flats each spring, and that some features persist until the entire soil mass has thawed, whereas others are washed away by tidal and wave action.

(2) Shilts (1978) documented mudboil activity in perennially frozen till, marine clayey silt, or other fine-grained sediments in Central Keewatin, Canada. During the early spring, mud, which normally has a low moisture content, becomes saturated, liquefies, and flows upward through

the permafrost and a desiccated sandy surface layer. As the thaw continues and the muds become less saturated, mudboil activity ceases.

Mudboils also have been attributed to tectonic forces:

(1) Westbrook and Smith (1983) discuss mudboil features near the Barbados Ridge (Caribbean Ocean), where accretionary sediment loading upon marine sedimentary deposits create extremely high pore-water pressures that force fine material upward.

(2) Ridd (1970) cites similar tectonic forces as a cause of mudboils in New Zealand, where abnormally high pore-fluid pressures in fine-grained deposits develop beneath the weight of overlying deposits.

Sand springs are more common, and generally longer lasting, than mudboils:

(1) Guhman and Pederson (1992) describe sand springs that are driven by artesian pressure and discharge water and coarser grained sand than is discharged from mudboils. The discharge vents generally are more stable than mudboil vents because the sides become mineralized or filled with large-sized sand and fine gravel.

(2) Gill and Kuenen, 1958; Burne, 1970; and Lowe, 1975 have found remnants of sand volcanoes (cones and vent tubes) in lithified sedimentary rocks in Ireland and Great Britain. The generalized theory of sand-volcano formation in this area is that they resulted either from the normal dewatering of an uncompacted (unconsolidated) sedimentation package or a delayed but rapid release of water from a fluidized unit that had been compacted by accretion of overlying fine-grained units. Lowe (1975, p. 161) states that the most easily liquefied sediments are coarse silt to fine-grained sand, which tend to be poorly cohesive, are moderately permeable, have little mass, and offer little frictional resistance to fluid drag.

Mudboils in the Tully Valley are similar to those described above, but are apparently longer lasting. The Tully Valley mudboils are volcanolike cones of fine sand and silt that range from several inches to several feet high and from several inches to over 30 ft in diameter. In active areas, the mudboils are dynamic ebb-and-flow features that can erupt and form a large cone in several days, then cease flowing, whereas others may discharge for several years. A mudboil may cease to flow if the vent becomes squeezed shut through land subsidence or becomes clogged with sediment. When a vent closes, a new vent may appear along a nearby subsidence fracture because the fracture is the easiest path for artesian flow and sediment to reach land surface.

The history of mudboil activity in the Tully Valley can be traced back for nearly 100 years; a detailed documentation is given in chart form in appendix 1. A newspaper article from the Syracuse (N.Y.) Post Standard, dated October 20, 1899, states:

> Few people are aware of the existence of a volcano in this town. It is a small one, to be sure, but very interesting. In the 20-rod gorge where the crossroad leads by the Tully Valley grist mill the hard highway bed has been rising foot after foot till the apex of a cone which has been booming has broken open and quicksand and water flow down the miniature mountain sides. It is an ever increasing cone obliterating wagon tracks as soon as crossed. The nearby bluff is slowly sinking. Probably the highway must sometime be changed on account of the sand and water volcano, unless it ceases its eruption.

The above account accurately describes the Tully Valley mudboils and presages the collapse of the Otisco Road bridge 92 years later, in 1991; it also indicates that land subsidence was already occurring. Such subsidence may indicate that the mudboil referred to was not the first in this area. During the early 1900's, the USGS did a "postmaster" survey of the water resources of Onondaga County, in which local postmasters were asked to respond to a 1-page questionnaire concerning springs, artesian wells, and other ground-water phenomena. The only reference to possible mudboil activity was found on an undated map, annotated by USGS personnel to indicate the location of "sand springs" near the Otisco Road bridge. No other information on this map citation could be found.

Acknowledgments

Thanks are given to the many State and local agencies who supplied background data and research guidance, including the New York State Department of Environmental Conservation - Division of Mineral Resources, who provided technical and historical data, and the Division of Water, who provided its drilling rig and crew for drilling freshwater-aquifer wells along Onondaga Creek, and to the members of the Mudboil Working Group of the Onondaga Lake Management Conference who provided a wide range of technical expertise. Allied-Signal is also acknowledged for permitting access to the mudboil areas on their property and providing historic records from the solution-mining operations at the brine field. Individual appreciation is extended to Roger Waller, USGS retiree, for access to his personal notes on mudboil activity from the mid-1970's through the late 1980's; to the Kuss family, who collected daily sediment samples and provided logistical support throughout the project; and to the residents of the Tully Valley who volunteered for collection of data in this study.

Thanks also are extended to the following individuals, who collected and(or) analyzed mudboil data under the USGS Volunteers for Science Program:

Valerie Holiday	Historical timeline (appendix 1) and literature review
John Marci	Onondaga Creek corridor mudboil characterization
Christopher Walbrecht	Onondaga Creek corridor mudboil characterization
Ethan Swift	Photo analysis of the mudboil/ depression area
Nicolas Yolsan	Preparation of graphs and tables
Meghan Hodgins	Historical timeline (appendix 1) and literature review
Matthew LaForce	Chloride concentrations from unconsolidated sediments
Daniel Bove	Numerical modeling of the mudboil/depression area
Devin Shay	Meteorological data analysis, strike/dip calculations

METHODS OF INVESTIGATION

This study entailed (1) review of local water-well records and published information from the brine field at the southern end of the valley and other regional hydrologic studies, (2) collection of streamflow, water-quality, and sediment-concentration data above and below the MDA on Tributary 6 of Onondaga Creek, (3) test-well drilling to define the local glacial stratigraphy and the extent of the aquifers driving mudboil activity, and their hydraulic conditions, and (4) compilation of geologic sections of the unconsolidated deposits and bedrock. Field methods of surface-water, ground-water, and precipitation-data collection, and of test-well drilling in surficial deposits and bedrock, are described in the following sections.

Surface Water

Surface-water data were collected on Onondaga Tributary 6 above and below the MDA, to enable calculation of the discharge from the mudboils in the MDA and along Onondaga Creek to determine discharge of mudboils within the mudboil corridor.

Streamflow and sediment discharge of Tributary 6 were measured in Parshall flumes up- and downstream of the MDA (fig. 3). Both 3-in. and 12-in. flumes were used upstream of the MDA and were installed in a channelized part of a wetland —the 3-in. flume was used during base-flow periods, and the 12-in. flume was used during high-flow periods, when the capacity of the 3-in. flume was exceeded. The flumes were placed in the only location where flow from upstream and from a spring-fed drain tile could be measured accurately. The wetland is flat and has several braided channels that flow into the MDA.

The flume downstream of the MDA (9-in. Parshall flume) was installed where the streambed gradient was steep enough to prevent backwater from any sediment bar that might form within or just below the flume. The large sediment load necessitated constant maintenance of the flume and stilling well.

Stream Discharge

Discharge of Tributary 6 (which flows through the MDA) was measured in accordance with procedures outlined by Kilpatrick and Schneider (1983) for use of Parshall flumes. The flumes were checked annually for the effects of frost heave, which were evident to some degree each spring, as well as intermittent washover from extremely high flows. Adjustments were made to the flumes and the surrounding backfill materials as needed. Discharge measurements were made by current meter to verify the flume ratings and to extend the ratings for high flows that overtopped or bypassed the flumes. The

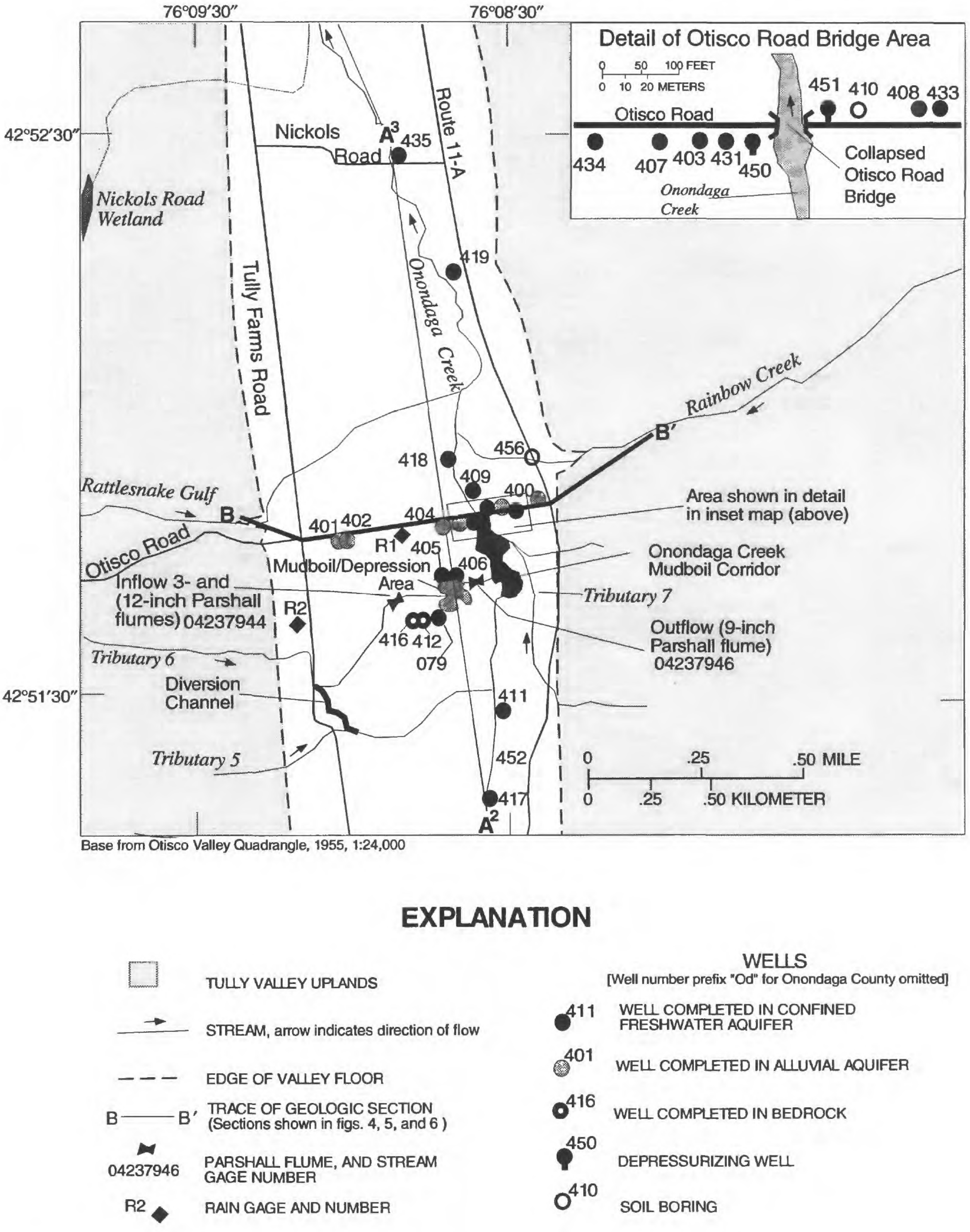


Figure 3. Locations of wells, Parshall flumes, rain gages, and geologic sections A^2–A^3 and B-B'. (Location is shown in fig. 2. Geologic sections are shown in figs. 4, 5, and 6.)

data were analyzed in accordance with procedures outlined by Buchanan and Somers (1968).

The discharge of mudboils within the Onondaga Creek corridor was calculated from streamflow measurements made on Onondaga Creek during base-flow periods in the fall of each year. Current-meter measurements were made just upstream of the mouth of in Tributaries 6 and 7 (a small channel entering Onondaga Creek from the east side of the valley, fig. 3), and on Onondaga Creek just above the mudboil corridor. The sum of these three flows was subtracted from the measured flow of Onondaga Creek downstream from the Otisco Road bridge to obtain the inflow from mudboils within this corridor. Discharge from the large mudboil that caused the collapse of the Otisco Road bridge during the summer of 1991, as calculated from streamflow measurements made just above and below that mudboil, was about 0.18 ft^3/s.

Flow measurements were also made in Rattlesnake Gulf and Rainbow Creek (fig. 3) to determine whether these streams lose water to the underlying unconsolidated deposits during the late summer and fall and supply the aquifers that drive mudboil discharge. The upstream measurement site was just downstream from the last bedrock exposure in each stream channel. (In Rattlesnake Gulf, the bedrock channel ends abruptly at an altitude of about 620 ft, whereas in Rainbow Creek it is intermittently exposed to an elevation of about 640 ft.) The downstream measurement sites were at an appropriate channel cross section about 1,300 ft from the corresponding upstream measurement site.

Suspended-Sediment Concentration and Chemical Quality

Samples of suspended sediment from the MDA were collected at the downstream flume during water years 1992-95 by an observer trained in collection techniques as outlined by Guy and Norman (1970). Samples were depth integrated throughout the centroid of flow in the diverging downstream section of the flume. During low flows, samples were collected daily and depth integrated by hand because the sampler does not permit sampling the lower part of the water column. During stormflows and periods of high runoff, a DH-75-Q[1] sampler was used to collect samples by the same technique. All sediment analyses were analyzed at the USGS Sediment Laboratory in Lemoyne, Pa. Water samples were collected monthly upstream and downstream of the MDA for chemical and physical analyses in 1992-94; thereafter, samples were collected once every 3 months. Samples were again depth integrated throughout the centroid of flow in the diverging section of the flume, and were collected in a glass quart container and composited in a USGS churn splitter. Aliquots were withdrawn, and samples to be analyzed for total constituent concentration were taken first; samples to be analyzed for dissolved constituent concentrations were then filtered directly into their containers. About 10 percent of the samples were collected as duplicates. All sampling equipment, including samplers, sampler nozzles, churn splitter, filters, and instrument probes were cleaned with deionized water between samples.

Water temperature, specific conductance, dissolved oxygen, pH, and barometric pressure were measured at the time of sample collection with a Hydrolab Series 4000 multi-parameter instrument. Field determinations of carbonate alkalinity ($CaC0_3$), carbonate ($CO_3^{=}$), and bicarbonate (HCO_3^-) concentration were made by incremental titration. All other analyses were made at the USGS National Water Quality Laboratory in Denver, Co.

Ground Water

A total of 25 holes were drilled in unconsolidated deposits to provide detailed data for construction of a geologic section across the valley along Otisco Road, and a geologic section down the valley axis along Onondaga Creek. Most of these holes were completed as monitoring wells to measure the hydraulic head in the upper sand-and-gravel aquifer or in the upper part of the underlying, confined, silt-and-sand aquifer.

Water Levels

Water levels in seven 2-in. inside-diameter (i.d.) PVC monitoring wells installed along Otisco Road were measured monthly to define the water-table configuration in the surficial sand and gravel aquifer(s) and determine whether the aquifers are recharged by the Rainbow Creek and Rattlesnake Gulf. Water levels in twelve 3-in. i.d. steel monitoring wells were also measured monthly. Commercial 30 lb/in^2 "Grade-B" pressure gages were used to measure hydraulic head in these wells; these gages

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[1] Use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

had an accuracy of ±3 percent of span, or about 1 lb/in^2 (2.3 ft). Several of the pressure gages were calibrated against a Meri-Cal portable digital manometer-calibrator and were found to be within the stated accuracy range. The pressure measurements were converted to elevation head for comparison with heads in the shallow zone wells. Heads in the deeper zones were measured in a similar fashion, but the density differences in these brackish waters were not converted to a freshwater-head equivalent because the limited water-quality sampling in this zone indicated variable water chemistry.

A pair of depressurizing wells was installed along Otisco Road in late 1993—one on either end of the collapsed bridge (fig. 3). The change in hydraulic head due to discharge from the depressurizing wells was monitored in three wells drilled 35, 70, and 195 ft from the western depressurizing well. Vibrating-wire transducers were lowered 12 ft below the top of casing for continuous data collection with an electronic data-logger.

Water Quality

Initially, only water samples taken during the deep-test-well drilling program were analyzed. These samples were collected from well Od-416—two zones in the unconsolidated deposits and four water-bearing zones in the bedrock. Because these intervals were under artesian pressure, each water-bearing zone was allowed to flow until temperature and specific conductance readings stabilized. The USGS collected and split the water samples for independent analyses by the New York State Department of Environmental Conservation and the former brine field operator. Later, the two depressurizing wells along Otisco Road were included in the water-quality testing. The protocols for collection and preservation of water samples in the surface-water quality program were followed in this program.

Precipitation

Although the area surrounding the Tully Valley contains several precipitation stations, differences in elevation of each gage above the Tully Valley floor were considered significant enough to warrant installation of two recording gages in the study area—a tipping-bucket gage on Otisco Road in the central part of the valley (altitude 570 ft), and a weighing-bucket gage at the western valley wall (altitude 620 ft) (fig. 3). Data collected in the valley were compared with data from nearby National Weather Service gages to determine whether the precipitation amounts were similar. The Syracuse Airport gage (altitude 410 ft), about 20 mi north of the Tully Valley, has the longest record in the area (101 years); two gages within 5 mi of the Tully Valley, Tully 4 NE (altitude 1,300 ft) and Tully - Heiberg Forest (altitude 1,900 ft) have shorter records. Comparison of the monthly precipitation data from these gages indicates substantial differences between the amount of precipitation measured on the valley floor and the amount at gages outside the valley. Regression analysis of total monthly precipitation indicated that the Syracuse Airport gage had the best correlation with the Tully Valley gages; therefore, the Syracuse Airport data were used for all long-term comparisons of precipitation data.

Test-Well Drilling

Initial information on unconsolidated deposits and bedrock consisted of a few drillers' logs of shallow domestic wells finished in unconsolidated deposits and more detailed bedrock logs for wells in the salt-solution-mining field, 1 to 4 mi upstream (south) of the MDA. Several test-holes were drilled to define the stratigraphy and hydraulic character of the unconsolidated deposits. Shallow holes were drilled (1) along Otisco Road to develop a cross-valley geologic section, (2) along Onondaga Creek to determine the extent of the various deposits along the axis of the valley, and (3) around the MDA to characterize the sediments in this area (fig. 3). The OLMC also commissioned the drilling of a deep test well just southwest of the MDA to determine the extent and nature of the entire unconsolidated sequence and to characterize the bedrock through the evaporite (halite) beds near the MDA.

Surficial Sediments

Test holes were drilled, and split-spoon samples were collected at 5-ft intervals to define the stratigraphy of the unconsolidated sediments; also, seven 2-in.-i.d. PVC wells were installed to monitor water levels in shallow aquifer units. Shallow and deep wells were installed near the intersection of Otisco and Tully Farms Roads in coarse-grained sediments within the Rattlesnake Gulf alluvial fan (fig. 2). The alluvial deposits were found to be underlain by a continuous layer of fine-grained lacustrine clay, silt, and fine sand that was easily augured with the USGS drilling rig, but beneath this deposit was a very fine sand and silt deposit under artesian pressure. Once this unit was penetrated, fine sand, silt, and water quickly flowed up into the augers and made well installation impossible. Removal of the auger flights created a mudboil-like situation that could not easily be shut off. Therefore the hole was sealed with a large-diameter casing driven into the silty-clay unit, and a steel plate was welded on top of the casing. This well was later converted to a monitoring well.

This experience led to a modification in the drilling technique that provided control of the pressurized flow of water and fine-grained sediments. After the coarse-grained sediments and the silty-clay unit were penetrated, a 3-in.-i.d. flush-joint steel casing with drive shoe was installed inside the hollow-stem auger and pushed into the silty-clay unit. The inside of the casing was washed, and a 2-in.-diameter, 2-ft-long split-spoon sampler was lowered to the bottom of the casing and driven ahead of it. The split spoon was then removed and the sample examined while the steel casing was driven to the bottom of the sampled interval. The casing was then cleaned out, and the process repeated until the artesian unit was found.

As the artesian unit was penetrated, sand and silt rose 30 or more feet up into the casing, and water began to flow from the top of the casing above land surface. The well was capped and fitted with a pressure gage that allowed measurement of hydraulic pressure within the artesian unit. In several wells a 1.5-in. PVC pipe with a soil-cloth-wrapped screen was installed inside the 3-in. casing, and a foot valve at the bottom of the screen allowed the PVC pipe string to be jetted into the fine sand below the steel casing to allow direct measurement of hydraulic head in the artesian unit at that altitude. The well was capped, and a pressure gage was attached to indicate downhole pressure in this unit. During the fall of 1993, the upper part of these artesian wells were filled with vegetable oil to reduce the chance of freezing and allow measurement of artesian pressures throughout the winter.

Bedrock

The OLMC recommended drilling a deep test hole to determine (1) the integrity of the bedrock and salt beds beneath the MDA, and (2) whether the unconsolidated sediments provide a hydraulic connection from the bedrock to the mudboils in the MDA. (This test hole was contracted and drilled under the direction of the OLMC.) The initial 4-in. pilot hole (Od-412) was drilled and sampled at 10-ft intervals to define the stratigraphy of unconsolidated deposits down to the top of bedrock, and was then finished as a 460-ft deep, 2-in. observation well in the upper bedrock. Later the casing was perforated and the hole cemented because the drillhole acted as a mudboil vent. An adjacent test hole (Od-416) was drilled, with multiple casings, until an 8 5/8-in.-i.d. casing was seated in the upper bedrock. The bedrock was then cored with a 98-percent recovery of shale, limestone, and evaporite deposits to a total depth of nearly 1,100 ft. Several hydraulic tests were performed at major water-bearing zones, water samples were collected from these zones for chemical analysis, and a series of borehole geophysical logs were collected. The bedrock section of the hole was drilled through the entire salt interval into the top of the Vernon Shale (fig. 4). After hydraulic tests were completed and water samples collected from the bedrock, this section was cemented up to the bedrock surface. Two permeable zones in the unconsolidated deposits had been identified in the pilot hole; therefore the casings in the bedrock well (Od-416) were perforated at these locations. Water samples were collected from these permeable units, and the hole was finished as a dual-completion, hydraulic-head-monitoring well.

HYDROGEOLOGY OF THE TULLY VALLEY

The Tully Valley hydrogeologic system is a result of the glacial processes of valley widening and deepening, and the subsequent deposition of unconsolidated sediments. The locations of mudboils in the valley, and their rate of discharge, reflect (1) the relation of the gently southward dipping bedrock to the stratigraphy of the overlying unconsolidated units, (2) the extent and hydraulic properties of these units, and (3) the locations of major side valleys and their hydraulic connection to unconsolidated units in the Tully Valley. Remediation of mudboil activity and attendant land subsidence will require a detailed analysis and correct interpretation of the entire hydrogeologic system.

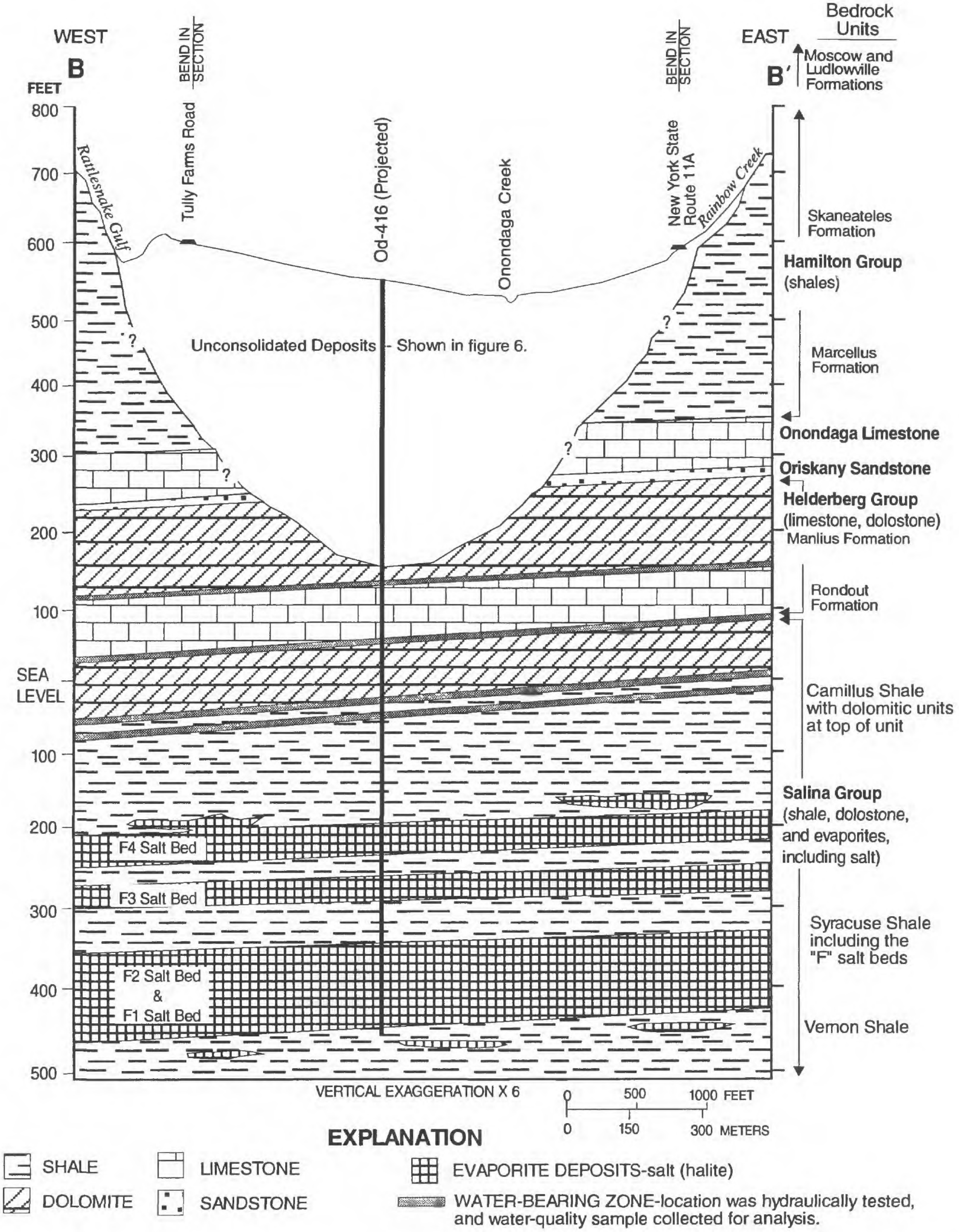


Figure 4. Geologic section B-B′ showing major bedrock units below Rattlesnake Gulf and Rainbow Creek from lower valley walls to top of Vernon Shale. (Modified from Getchell, 1982, plate 1. Location of section is shown in fig. 2.)

Bedrock

The Tully Valley lies within and above bedrock units that span the Middle Devonian through Upper Silurian ages. The bedrock is primarily shale but has units of limestone, dolomite, siltstone, and very minor beds of sandstone. Ground water in these units moves in the weathered upper bedrock, along fractures and in bedding planes that are generally found at major lithologic changes. The stratigraphic sequence studied in this project lies between the Tully Limestone, at the top of Bare Mountain, and the top of the Vernon Shale, which is just below the Salina Group salt beds (fig. 4).

Stratigraphy

The bedrock ridges that are exposed 1,000 to 1,200 ft above the Tully Valley floor consist of shale, limestone, and siltstone of Middle Devonian age (Rickard, 1975). Bare Mountain (locally known as Bear Mountain), on the west side of the valley and north of Otisco Road (fig. 1), is capped Tully Limestone, which overlies the Hamilton Group Shales, a sequence of shales with minor interbedded limestone units. The Hamilton Group forms the valley walls and underlies the present valley floor to a depth of 300 ft (fig. 4). Below the Hamilton Group lies the Onondaga Limestone Formation, the Oriskany Sandstone, and the Helderberg Group of limestones and dolomites. Onondaga Limestone, which constitutes the floor of most buried valleys in the Finger Lakes region, acted as an erosion-resistant ramp that the glaciers followed downward along the regional dip (Dr. Henry Mullins, Syracuse University, oral commun., 1994).

Unlike most valleys in this region, the Tully Valley near the MDA has been glacially eroded down to the middle of the Helderberg Group (416 ft below land surface) within the Manlius or Rondout formations, as indicated by drillhole data from the OLMC deep test well (Brayton Foster, private consultant, written commun., 1993). Below the Helderberg Group lies the Upper Silurian Salina Group and the Syracuse Formation, which consists of shale, dolomite, and the evaporite (halite or salt) deposits (fig. 4) that have been solution-mined in the southern part of the valley. The halite deposits are part of an extensive evaporite sequence from central New York to Illinois.

In New York, the northern edge of the Salina salt units is just north of the Tully Valley (Rickard, 1975). Leutz, (1959) in describing the stratigraphy of the Salina Group outcrop near Syracuse, indicated that the salt intervals near Tully grade northward into two clay members that contain gypsum and relict salt crystals. The clay members, here referred to as the "upper" and "lower" clays, constitute about a third of the corresponding salt thickness beneath the Tully Valley (Leutz, 1959, p. 65). Evidence from three deep gas wells drilled in a north-south line, west of the Tully Valley (Od-453, 454, and 455 in fig. 1) corroborate the northern extent and southward thickening of the salt beds. No salt was reported in well Od-455 near Cedarvale (fig. 1), and the thickness of the Syracuse Formation is 261 ft. The log for well Od-454, west of Cardiff, reported only three salt beds with a total salt thickness of 131 ft, and a total Syracuse Formation thickness of 380 ft. The southernmost well (Od-453), northwest of the Tully Lakes, penetrated four saltbeds with a combined thickness of 222 ft and a total Syracuse Formation thickness of 484 ft. Subtracting the salt thickness at wells Od-454 and Od-453 from the total Syracuse Formation thickness yields the shale thickness found at well Od-455, which had no salt.

The total thickness of the saltbeds at the OLMC deep well (Od-416) next to the MDA was 152 ft, and the thickness at the solution-mining field, ranged from 150 ft at the north end of the field to nearly 200 ft at the southern end (fig. 5), indicating that the salt layer thickens to the south. Beneath the salt beds is the distinctive red-green Vernon Shale, which contains a distinctive red-stained salt and was the lowest stratigraphic sequence studied.

Strike and Dip

Nearly 100 years of solution mining and subsidence have increased the complexity of the structural deformation in the Tully Valley. Data on bedrock structure are limited mostly to the Tully Valley brine field and from the OLMC deep well (Od-416) and several bedrock exposures along the valley wall.

The Hamilton Group sequence in the Tully Valley dips 25° to the southwest at about 48 ft/mi, as inferred from the Centerfield Member of the Hamilton Shale studied by Grasso (1966). Cooper (1930) estimated a similar regional southwestward dip of 45 to 50 ft/mi. The strike and dip of several stratigraphic units were analyzed in this study to obtain an indication of local structure in the Tully Valley. This entailed using the three-point method of Compton (1985) at 10 wells in

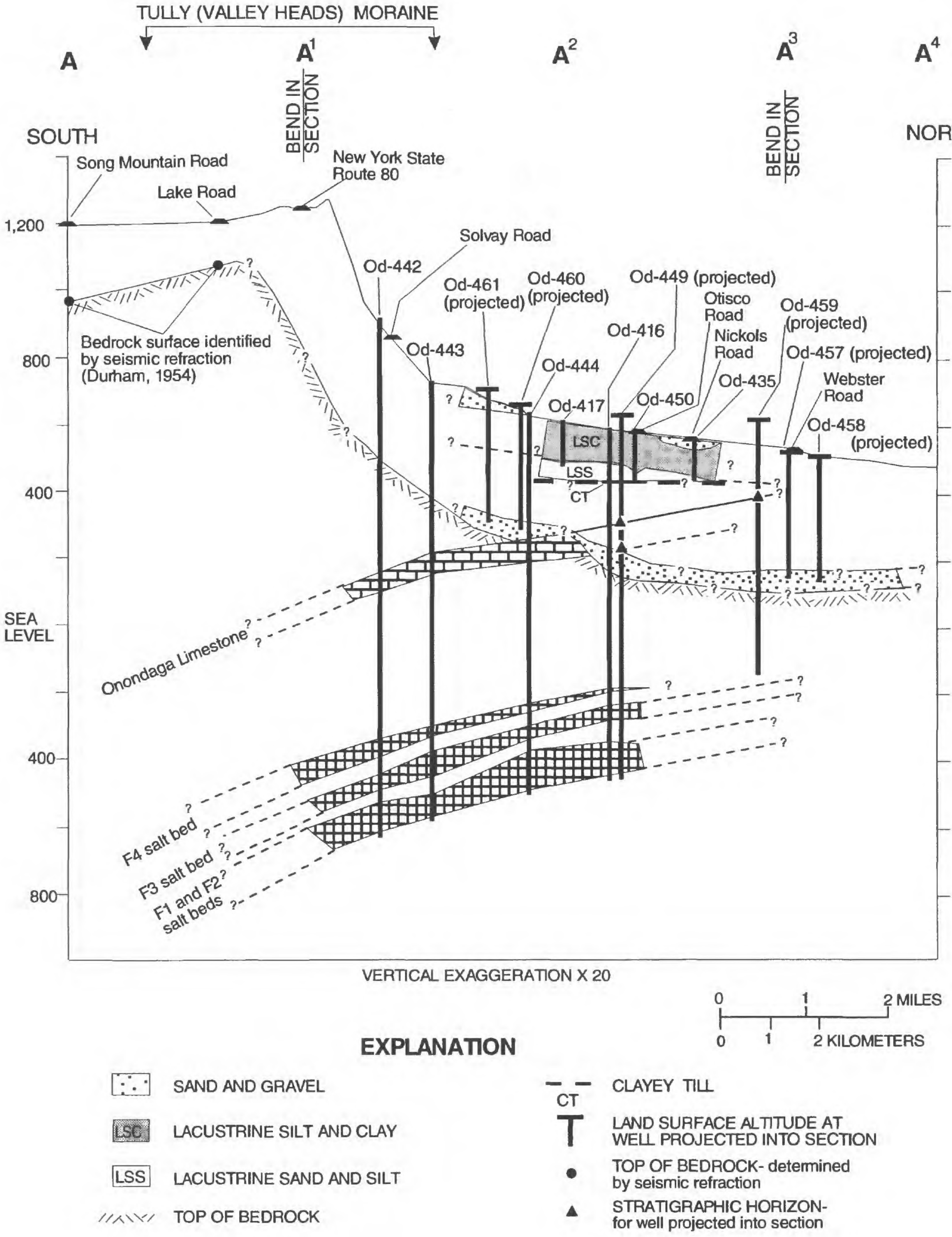


Figure 5. Geologic section A-A^4 from Tully Lakes through middle part of Tully Valley, showing position of Salina "F" salt beds, Onondaga Limestone, bedrock surface, and generalized unconsolidated units in mudboil area near Otisco Road. Location is shown in fig. 1.)

the valley and 3 wells outside the valley. In general, four strike-and-dip sets are present in the Tully Valley—two above the Syracuse Formation and two below. In the valley and above the Syracuse Formation, the strike is N. 48° E., with a dip of 71 ft/mi to the southeast. Additional information from deep wells west of the valley (wells Od-453, Od-454, and Od-455), indicate that the strike changes to N. 75° W. with a dip of 83 ft/mi to the southwest. Data from within and below the Syracuse Formation are more limited, but the in-valley strike for the top of the third saltbed is N. 27 ° E. with a dip of 89 ft/mi to the southeast, whereas the local strike at the top of the Vernon Shale is N. 48° W. with a dip of 58 ft/mi to the southwest. The reasons for the change in strike and dip is unknown, but the change indicates that the differences in measured strike and dip could be due to (1) localized folding above and below the décollemont surface (within the saltbeds) from tectonic stresses, (2) localized upwarping (Matheson and Thomson, 1973, and Molinda and others, 1992) from the removal of 1,200 ft of bedrock from the valley floor by glaciation, and(or) (3) recent glacial rebound.

Near-Vertical Fracture Patterns

Isachsen and McKendree (1977) identified linear features from aerial and satellite imagery on a brittle-structures map of New York State and noted a north-south linear feature along the axis of the Tully Valley as well as an east-west feature that crosses the valley in the vicinity of Rattlesnake Gulf and Rainbow Creek side valleys. Getchell (1983) measured two major joint sets, N. 8° W. and N. 80° E., which roughly coincide with DeGroffs' (1950) Set "1" at N. 10° W. to N. 10° E. and Set "2" at N. 60° to 90°W.

Smith (1935), Phillips (1955), and Chute (1964) mapped bedrock thrust faults striking N, 65° to 75° W, several miles north of the Tully Valley. Haley & Aldrich of New York (1991) described a fault surface striking N. 74° W. with a dip of 32° to the southwest in the southern part of the Tully Valley near Solvay Road (fig. 2); this structure apparently crosses the valley and extends through the east and west brine-field areas. They also described another possible fault that generally strikes north-south and probably is in or near the eastern part of the solution-mining field.

Several north-northwest-trending bedrock fractures on the east-facing, upper slope of Bare Mountain, north of Otisco Road, appear as vertical bedrock walls that strike N. 7° W. and extend laterally several hundreds of feet in the Tully Limestone and in various sections of the upper Hamilton Shales. These features probably are tensional features parallel to the dominant regional joint set (Dr. Daniel Karig, Cornell University, written commun., 1994).

In summary, regional dip of all bedrock units is southwest to southeastward at 45 to 89 ft/mi. A major north-south trending fracture set appears on the upper, east-facing slope of Bare Mountain and may pass through or near the eastern area of the brine field at the southern end of the Tully Valley. Several orthogonal fractures may cross the north-south fracture set near Solvay and Otisco Roads, and others may be present further to the north. Changes in the strike and dip in bedrock units above the saltbeds in the southern end of the Tully Valley may be related to localized folding or upwarping of the bedrock surface and may be enhanced by 100 years of solution mining in the brine field.

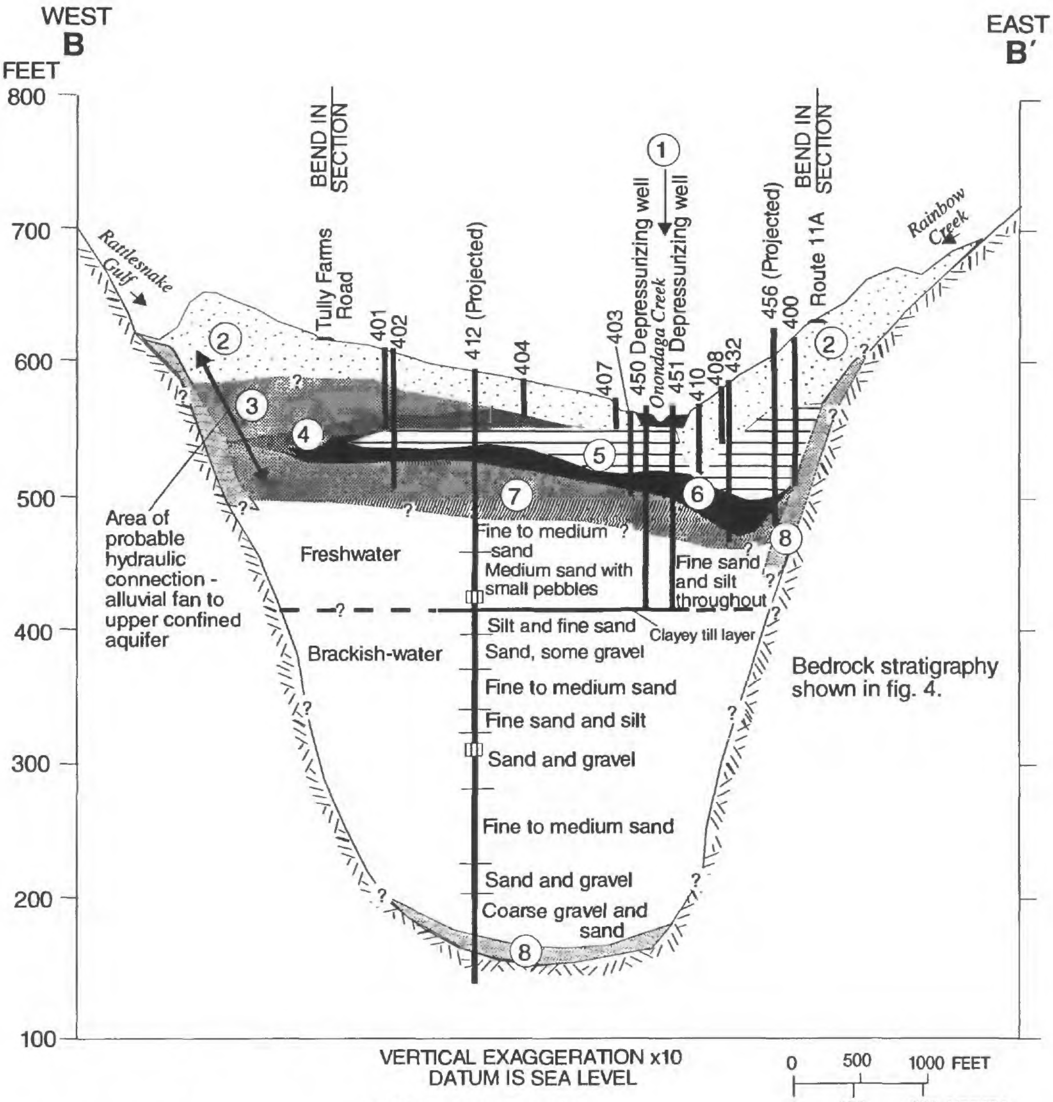
Unconsolidated Deposits

Repeated glaciations widened and deepened the preglacial valley that now forms the Tully Valley, and the bottom part of the valley became filled with over 400 feet of unconsolidated deposits during deglaciation. The OLMC exploratory hole (Od-412) is the only boring from which a detailed description of the entire sequence of unconsolidated deposits is available. The split-spoon samples from this location indicate that at least two major advances and recessions of ice, and probably several minor ones, occurred during the last glacial period.

Tully Valley Sequence

The exploratory hole southwest of the MDA (Od-412) penetrated about 420 ft of unconsolidated deposits above bedrock. Two sequences of upward-fining deposits were indicated and probably are representative of the generalized glaciolacustrine stratigraphy for the Tully Valley (fig. 6) from the Tully Moraine to its junction with the west branch of Onondaga Creek north of U.S. Route 20 (fig. 1).

The lowermost unconsolidated unit consists of a dense, clayey sand and gravel that is interpreted as till overlain by beds of coarse sandy to bouldery gravel with some interbeds of silt. The coarse-grained unit over the till was probably deposited by meltwater from the base of the glacier. Subsequently, glacial Lake Cardiff (Grasso, 1970) formed between the steep valley walls, the moraine to the south, and



EXPLANATION

ALLUVIAL DEPOSITS

① FLOODPLAIN AND MUDBOIL DEPOSITS - Silt, sand and gravel deposited by Onondaga Creek and upstream mudboils.

② FANS - Sand and gravel deposited by Rattlesnake Gulf and Rainbow Creek.

LACUSTRINE DEPOSITS

③ LAMINATED SAND AND SOME SILT/CLAY - Mostly fine to medium sand interbedded with minor amounts of silt and clay deposited by Rattlesnake Gulf as it flowed into a proglacial lake.

④ LAMINATED SAND AND SILTY-CLAY - Approximately equal parts of very fine sand interbedded with silty-clay that settled-out further in the proglacial lake.

⑤ LAMINATED SILTY-CLAY WITH SAND - Mostly silty-clay interbedded with occasional layers of medium-to-fine sand that settled out furthest in the proglacial lake. Coarser sand is found along Otisco Road; finer sand-to-silt wisps are found further north and south of Otisco Road. Forms top of confining unit over liquifiable sand and silt unit in the mudboil areas.

LACUSTRINE DEPOSITS (cont'd)

⑥ CLAY AND SILT - Massive unit that generally covers most of valley floor north and south of mudboil areas. Forms confining unit over upper aquifer and grades from clay at surface to silt at depth.

⑦ SILT AND SAND - Massive, grading from silt and very fine sand at the top to medium to coarse sand and fine gravel with silt at bottom of unit. Unit is under artesian pressure and forms upper confined aquifer.

OTHER GLACIAL DEPOSITS

⑧ TILL - A dense unit of sand, gravel,and boulders embedded in a clay matrix. This unit may underlie entire glacial sequence in the valley.

BEDROCK

410 WELL AND NUMBER, without "Od" prefix

MONITORING ZONE PERFORATED IN STEEL CASING, perforated after hydraulic testing of deeper bedrock zones and grouting of the bedrock section of deep well On-416.

Figure 6. Geologic section B-B′ showing upper unconsolidated deposits along Otisco Road and deeper unconsolidated deposits projected from well On-412, southwest of mudboil/depression area. (Location of section is shown in figs. 2 and 3.)

the receding ice front to the north and allowed fine sand, silt, and clay to settle to the lake floor and cover the coarser sand and gravel deposits. The fine-grained unit graded laterally southward from coarse sand to silt to clay with increasing distance from the retreating ice front. When the ice front reached the northern end of the valley (near U.S. Route 20) it readvanced toward the Tully Moraine, compacting a fine-grained clay unit into a 10-ft thick layer of dense clay till. This till layer, at an altitude of 430 ft near the MDA and along Otisco Road, apparently separates a lower (brackish-water) aquifer from an upper (freshwater) aquifer.

The glacier again receded northward, and meltwater deposited another sequence of coarse to fine gravel above the clayey till layer; this younger layer grades upward to a medium- to very-fine sand. About 60 ft below land surface, the sequence blends to a lacustrine unit with gray silt at the bottom and fining to a red-brown clay near land surface. This upper silty-clay unit has not been compacted. Most of the drill holes penetrated a zone near the middle of this unit that is so soft that split-spoon samples were collected by pushing the spoon into the material by hand. Soil samples from drill hole Od-435 near Nickols Road and Onondaga Creek were analyzed for Atterberg Limits; results are given in table 1. The Atterberg limits are a measure of the change in soil when water is added—the change from a solid, to a semisolid, to a plastic, or to a liquid material. The plasticity index is the difference between the plastic and liquid limits; the liquidity index is a measure of soil sensitivity (ability to become a flowing material). Some of the samples represented in table 1 are at or beyond their liquid limits.

X-ray-diffraction analysis of clay minerals in six soil samples from selected locations and depths in the Tully Valley (table 2) indicate that the predominant clay minerals are illite, chlorite, and quartz with minor amounts of calcite and dolomite. These results are consistent with other analyses of soil samples from other sites in the glaciated valleys of central and western New York. Alluvial fans cover or interfinger with the silty-clay unit at the mouths of Rattlesnake

Table 1. Atterberg Limits Index results for split-spoon samples taken in test hole Od-435, along Nickols Road near Onondaga Creek, Tully Valley, N.Y.

[Soil tests by Dr. Dawit Nugussey, Department of Civil and Environmental Engineering, Syracuse University, 1994.]

Interval of sample (feet below land surface)	Water content (in percent)	Liquid lLimit (in percent)	Plastic limit (in percent)	Shrinkage limit (in percent)	Plastic index (in percent)	Liquidity Index
30-30.9	42.6	45.3	26.4	19.6	18.9	0.9
31-32.9	35.0	39.6	16.2	11.7	23.4	0.8
33-34.9	26.8	28.8	16.4	13.6	12.4	0.8
35-36.9	35.1	33.9	23.4	19.7	10.4	1.1
37-38.9	44.6	43.1	25.9	19.7	17.2	1.1
41-42.9	44.4	42.0	27.4	21.6	14.6	1.2
43-44.9	35.8	39.9	25.9	20.6	14.0	0.7
45-46.9	38.4	38.1	24.7	19.8	13.4	1.0
57-58.9	28.7	34.1	23.0	19.2	11.1	0.5
62-63.9	29.7	33.1	23.5	19.9	9.7	0.6
67-68.9	33.8	37.0	24.3	19.7	12.7	0.7
72-73.9	32.2	36.8	23.9	19.4	12.9	0.6
77-78.9	29.4	34.0	22.9	19.1	11.0	0.6
84-85.9	33.3	36.3	23.7	19.2	12.9	0.7
89-90.9	32.3	37.8	24.4	19.6	13.4	0.6
102-103.9	30.7	35.4	22.2	18.0	13.2	0.6

Table 2. Predominant clay minerals in core samples from selected locations and depths in Tully Valley, N.Y., in order of decreasing abundance.

[X-ray diffraction analysis by Dr. Patricia Costanzo, Department of Geology, State University of New York at Buffalo, 1995. ft, feet.

SAMPLE 1	SAMPLE 2	SAMPLE 3	SAMPLE 4	SAMPLE 5	SAMPLE 6
Intersection of Webster and Tully Farms Roads, 2-ft depth (near foot of Landslide 3)	East of Tully Farms Road, 2-ft depth (near foot of Landslide 4)	Upstream of mudboil/depression area at waterfall, ~2-ft depth (top of massive clay unit)	Well Od-450 at the 132-133-ft depth (top of clayey-till unit)	Well Od-416 at the 40-41-ft depth (within massive clay unit)	Backscarp of Tully Valley landslide (top of massive clay unit at exposed soil face)
Illite	Illite	Quartz	Illite	Illite	Illite
Quartz	Chlorite	Illite	Quartz	Quartz	Quartz
Chlorite	Quartz	Chlorite	Chlorite	Chlorite	Chlorite
Calcite	Calcite	Calcite	Dolomite	Dolomite	Dolomite
Dolomite	Dolomite	Dolomite	Calcite	Calcite	Calcite

Gulf and Rainbow Creek. These fans contain coarse-grained sand and gravel along the valley walls and probably interfinger with the coarser grained deposits below the silty-clay layer.

Rattlesnake Gulf and Rainbow Creek Sequence

As the ice front was discharging glacial and lake sediments into the main valley, Rattlesnake Gulf and Rainbow Creek were also discharging coarse- to fine grained materials into the main valley. The east-west geologic section B-B′(fig. 6) displays the stratigraphic sequence of coarser sand and gravel adjacent to the valley walls grading to fine sand and silt toward the middle of the valley.

The source of material in Rattlesnake Gulf was glacial deposits left on the hillsides as well as materials eroded from the bedrock walls of the side valley. Additional streamflow and sediment probably entered the Tully Valley from the Otisco Lake Valley to the west during early deglaciation, as indicated by remnants of two ice-margin channels along the west ridge of the Tully Valley (fig. 1)—the Vesper Channel (crest altitude 1,440 ft), which drained into Emerson Gulf at the south end of the valley, and the Otisco Channel (crest altitude 1,260 ft), which drained into Rattlesnake Gulf, just north of Otisco Road on the west side of the Tully Valley (fig. 2). This would have provided additional sediment to the Tully Valley and may have forced Onondaga Creek to flow along the east side of the valley after each glacial lake drained. The present watershed for Rainbow Creek is considerably smaller than the Rattlesnake Gulf watershed and probably contributed less alluvial material to the valley floor.

As coarse materials from Rattlesnake Gulf and Rainbow Creek were being deposited near the Tully Valley walls, the fine sand, silt and clay were settling into the central part of the lake, creating the lateral gradation from coarse to fine deposits toward the middle of the valley. The extent of these layered deposits is indicated in the east-west and the north-south geologic sections (figs. 6 and 7). The drilling logs of holes in the Otisco Road/Onondaga Creek area indicate that fine-grained sand layers are more numerous south of Otisco Road than north of it, and split-spoon samples from further north and south of Otisco Road indicate sand layers to be fewer and to contain very fine sand to silt-sized material. Logs from drill holes along Onondaga Creek (Od-411, south of Otisco Road, and Od-418, north of Otisco Road) do not indicate distinct layering but show thin, gray bands or wisps of silt within the upper part of the red silty-clay unit.

In summary, the layered fine sand, silty-clay sequence in this part of the Tully Valley was laid down during the last major recession of the ice front, when the valley contained a glacial lake. Coarser material was periodically deposited by both side streams onto the finer grained silty-clay lake floor, creating the layered deposit in the Otisco Road/Onondaga Creek area. More sediment was discharged from Rattlesnake Gulf than from Rainbow Creek because its watershed was larger and could have included early glacial-recessional drainage from the adjacent Otisco Lake valley.

Surface Water

The following discussion describes inflows to Onondaga Creek, with emphasis on (1) discharge from mudboils in the Onondaga Creek mudboil corridor and (2) discharge of Tributary 6 and mudboils in the MDA along Tributary 6.

Onondaga Creek Mudboil Corridor

The steep valley walls and their thin soil cover limit the infiltration of precipitation and lead to "flashy" runoff (rapid peaks and recessions) in Onondaga Creek and its tributaries during the spring of each year and after intense storms. Summer streamflow is sustained by ground-water discharge from bedrock along the valley walls and by springs at the Tully Moraine. The valley floor is underlain by relatively impermeable clay and silt that limit discharge from the ground-water system to Onondaga Creek. The alluvial-fan deposits of Rainbow Creek and Rattlesnake Gulf interfinger with the lacustrine deposits and allow water from these tributaries to infiltrate and recharge the aquifers along the valley walls. The Rattlesnake Gulf fan is much larger than the Rainbow Creek fan and, thus, provides a larger contribution to the aquifers on their respective sides of the valley.

The flood plain of the 1,500-ft reach of Onondaga Creek upstream of the collapsed Otisco Road bridge contains active mudboils, either in the form of individual vents or as large areas containing several indistinct vents, that discharge water and variable amounts of sediment to Onondaga Creek. Several less active mudboils are found further upstream (south); the vent of one such mudboil (mudboil 3, fig. 2), about 1,500 ft upstream of the mudboil corridor, destroyed a bridge that crossed Onondaga Creek in the early 1950's (John Snavlin, resident, oral commun., 1994), and activity at this small mudboil field increased during the summer of 1994 and continues (Richard Snavlin, resident, oral commun., 1995). Other sets of mudboil-like features (mudboils 1 and 2, fig. 2) were noted south of mudboil 3 (fig. 2), although these might represent old drain tiles whose discharge resembles that of a

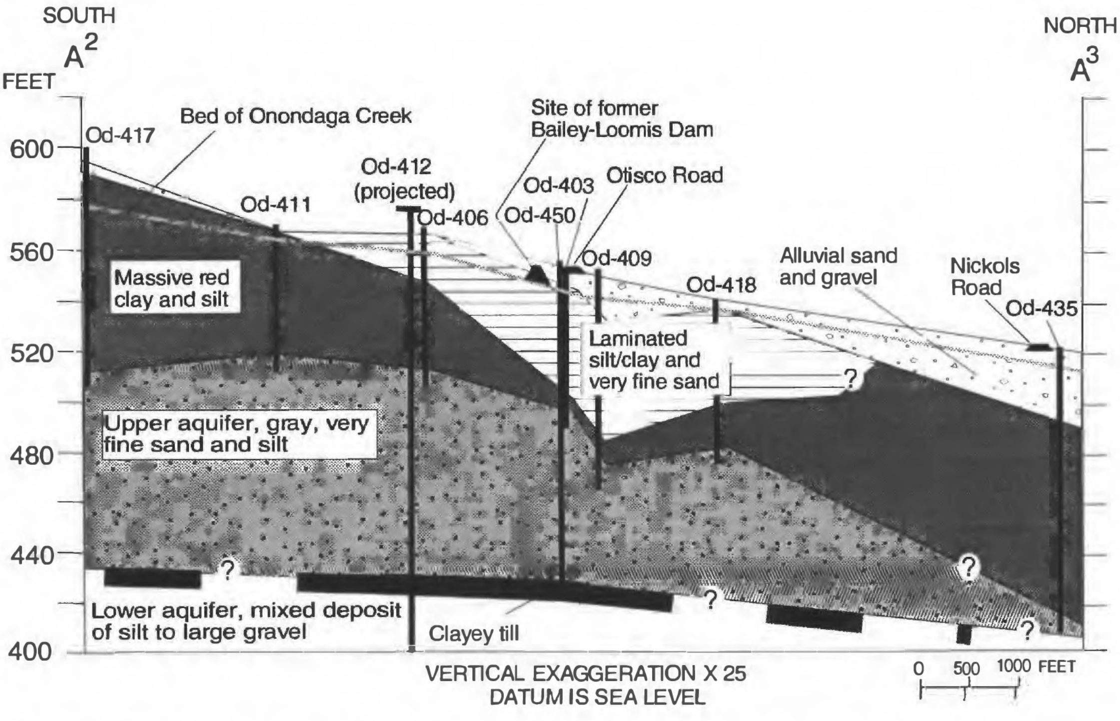


Figure 7. Geologic section A^2–A^3 showing unconsolidated deposits in central part of Tully Valley and projected thickness of confined freshwater aquifer between wells Od-417 and Od-435. (Location of section is shown in figs. 2 and 3.)

mudboil. Activity here was limited to two areas that are now small wetlands with only minor sediment discharge. Only one mudboil has been reported north of Otisco Road (mudboil 4, fig. 2); it was apparently short-lived because teenagers "playing on" the reported vent caused it to collapse and stop flowing. (Matthew Parks, resident, oral commun., 1993).

Discharge from the mudboil corridor is difficult to assess because the quicksandlike nature of the mudboil sediments near the vent makes discharge impossible to gage, and discharge from mudboil fields also is difficult to assess because it is too diffuse to measure and is partly lost through evapotranspiration before it can reach Onondaga Creek. Therefore, mudboil discharge to Onondaga Creek was estimated from discharge measurements made above and below the mudboil corridor in late September or October of 1991-95 (during the seasonal low-flow period and also after several heavy frosts) to minimize losses through evapotranspiration. The mudboil discharge would be small during this period but was used because discharge-measurement error is smallest when streamflow is lowest. Results of the measurements (table 3) indicate only minor discharges from the mudboil corridor during the 1991, 1992, 1993, and 1995 measurement periods, but a large increase in mudboil corridor flow–about 1 order of magnitude – in 1994. This increase could be attributed to several periods of heavy rain (2 in. or more in several hours) during the late summer and early fall of 1994, which could have recharged the freshwater aquifer and increased mudboil discharges along the corridor; an increase in mudboil discharge and the appearance of several new mudboils within the MDA were noted during this period. The drought of 1995 decreased discharge from mudboils, as evidenced by the lack of increased flow within the corridor and only limited mudboil activity in the MDA.

Tributary 6 and Mudboil/Depression Area (MDA)

Onondaga Creek Tributary 6 flows through the MDA, the area of most active mudboil flow and sediment discharge to Onondaga Creek, and the area of greatest land subsidence. Tributary 6 initially drained a 1.1-mi^2 watershed that contained part of the eastern side of Dutch Hill (fig. 2), but in July 1992, as a mudboil-remediation effort, about 70 percent of the drainage area upstream of the MDA was diverted south to Onondaga Creek Tributary 5, which enters Onondaga Creek south (upstream) of the MDA (fig. 3). This diversion, at Tully Farms Road (fig. 3), sharply decreased the amount of water flowing into the MDA and thereby reduced the amount of sediment flowing from the MDA to Onondaga Creek.

Discharge

The rate of flow leaving the MDA (inflow to the MDA plus mudboil discharge within the MDA) follows a seasonal pattern of peak discharge in the spring (averaging more than 3 ft^3/s) and a minimal discharge in the fall (generally less than 1 ft^3/s). The mudboils in the MDA do not respond to individual storms immediately, but the total MDA flow responds to periods of intense precipitation, although

Table 3. -- Calculation of discharge from mudboils within the Onondaga Creek mudboil corridor in Tully Valley, N.Y., 1991-95.
[All values are in cubic feet per second; + or - indicates gain or loss of flow in reach; dashes indicate wells were not discharging; Locations shown in fig. 3

Date	Discharge at upstream end of reach (a)	Mouth of Tributary 6 (b)	Mouth of Tributary 7 (c)	Depressurizing Wells (d)	Sum of columns a through d (e)	Discharge at downstream end of reach (f)	Calculated discharge from mudboils (col. f) minus (col. e)
October 30, 1991	4.11	0.460	0.073	---	4.64	4.82	+0.18
October 6, 1992	12.95	.540	.310	---	13.8	13.9	+.10
October 14, 1993	3.77	.330	.072	---	4.17	4.10	- .07
October 18, 1994	6.76	.544	.145	0.051	7.50	8.62	+1.12
September 20, 1995	2.82	.264	.030	.044	3.16	3.16	0.00

usually with a lag of several weeks. For example, about 10.4 in. of rain fell during July 1992, mainly during four large (1.5 in. or greater) storms interspersed among 10 additional days with at least 0.25 in. of rain each; the resultant increase in MDA flow is evident in fig. 8A. Similar periods of increased precipitation and mudboil flow during the summer of 1994 can be seen in fig. 8C. MDA flow also increased during April 1993 (fig. 8B), the time of the Tully Valley (LS-4) landslide; this corresponds to the period of spring recharge, which included the remnants of the March blizzard of 1993 and more than 7.5 in. of precipitation in April.

Diversion of flow from the upper 0.7 mi^2 of the MDA watershed in June 1992 decreased the inflow to the MDA and also decreased, by 2,000 ft, the length of stream channel that provided recharge to the southern part of the Rattlesnake Gulf alluvial fan east of Tully Farms Road (fig. 3). Although this reduction in recharge diminished summer inflow rates to the MDA during 1993-95, it did not affect the discharge rates of MDA mudboils.

Suspended Sediment

Suspended-sediment concentration in Tributary 6 and Onondaga Creek is directly related to mudboil activity in the MDA and, to a lesser extent, mudboil activity within the Onondaga Creek corridor. Suspended-sediment concentrations were measured frequently at the outflow flume, and suspended-sediment loadings to Onondaga Creek from the MDA were calculated to assess preremediation loads to the creek and the success of remediation projects in decreasing those loads. Particle-size analyses were also made to determine the distribution of sediment particle sizes leaving the MDA and to design appropriate methods to capture most of the sediment.

Concentration and Load.– Suspended-sediment concentration was measured in samples collected daily (and more frequently during high flows) by an observer during 1992-94; samples were collected weekly in 1995. No relation between mudboil activity and sediment concentration can be defined. Large surface-water discharges generally produce higher sediment concentrations than small discharges, except at the MDA, where concentration is inversely related to MDA outflow as a result of dilution during high flows from upstream, which had very low concentrations of sediment.

Suspended-sediment concentrations in water samples collected at the MDA outflow ranged from 17 mg/L to 31,200 mg/L during 1991-95. The largest concentrations occurred early during the 1992 water

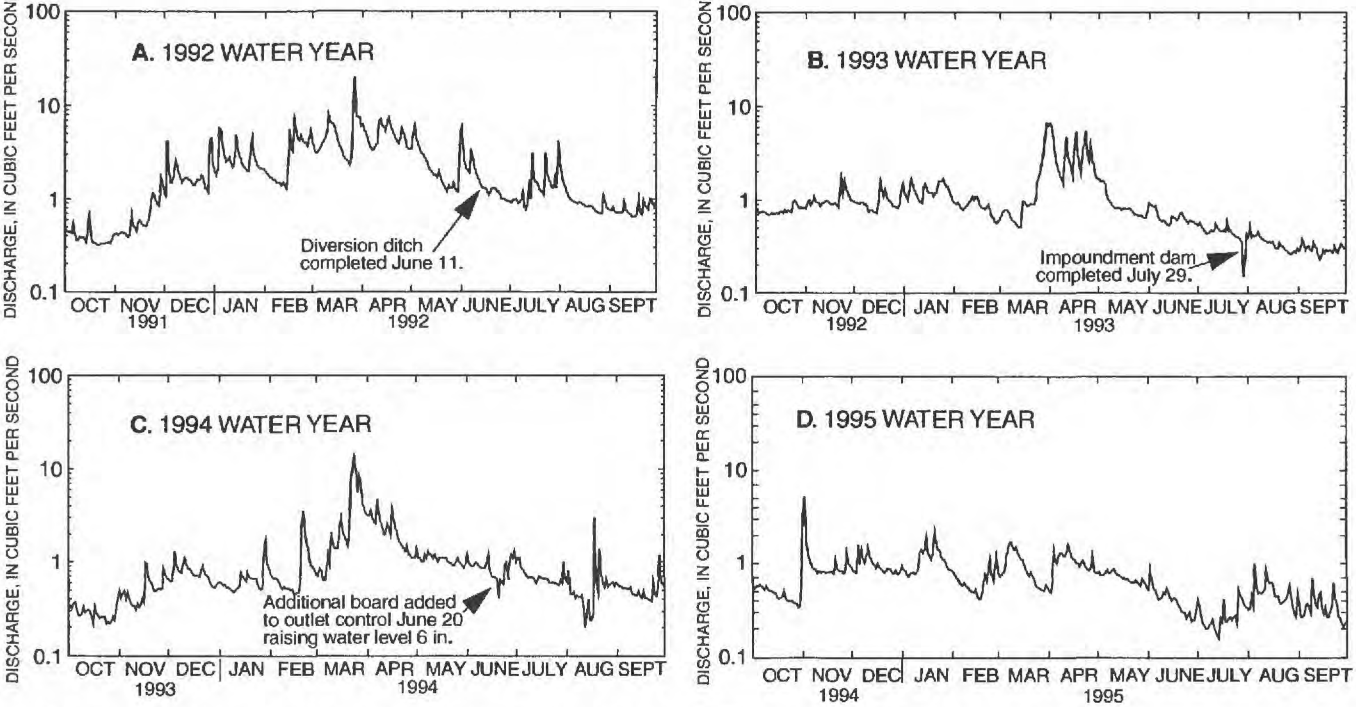


Figure 8. Hydrographs showing daily mean flow leaving mudboil/depression area, water years 1992-95.

year, when no remediation project was in place. The smallest concentration occurred after the upstream diversion and installation of the MDA impoundment in July 1993, which allowed the sediment to settle out. The range of daily mean sediment concentrations for each month of 1992-95 is depicted in boxplots in figure 9.

Suspended-sediment loads (tons per day) were calculated from sediment concentrations through a software program called CLOAD (William Rose, U.S. Geological Survey, written commun., 1991) that uses the daily mean streamflow and a straight-line interpolation between sample concentrations to calculate daily mean sediment concentration. Daily loads are then computed as the product of daily mean streamflow (in ft^3/s) and daily mean sediment concentration (in mg/L), multiplied by a conversion factor (0.0027) to obtain daily mean sediment load (in tons).

Sediment loads, in contrast to sediment concentrations, are usually greatest during periods of high discharge because the increased quantity of flow more than compensates for the effect of dilution. The largest monthly sediment load occurred during March 1992, when Tributary 6 delivered 2,119 tons (an average of 68 tons per day) to Onondaga Creek. Like the smallest concentrations, the smallest sediment loads occurred soon after the impoundment at the outlet of the MDA was in operation. Total monthly sediment loads from the MDA and the corresponding discharges for water years 1992-95 are plotted in figure 10. The daily mean sediment load from the MDA for 1992-95 was 10.7 ton/d, and mean daily loads for water years 1992, 1993,1994, and 1995 were 29.8, 9.75, 1.41, and 1.80 ton/d, respectively.

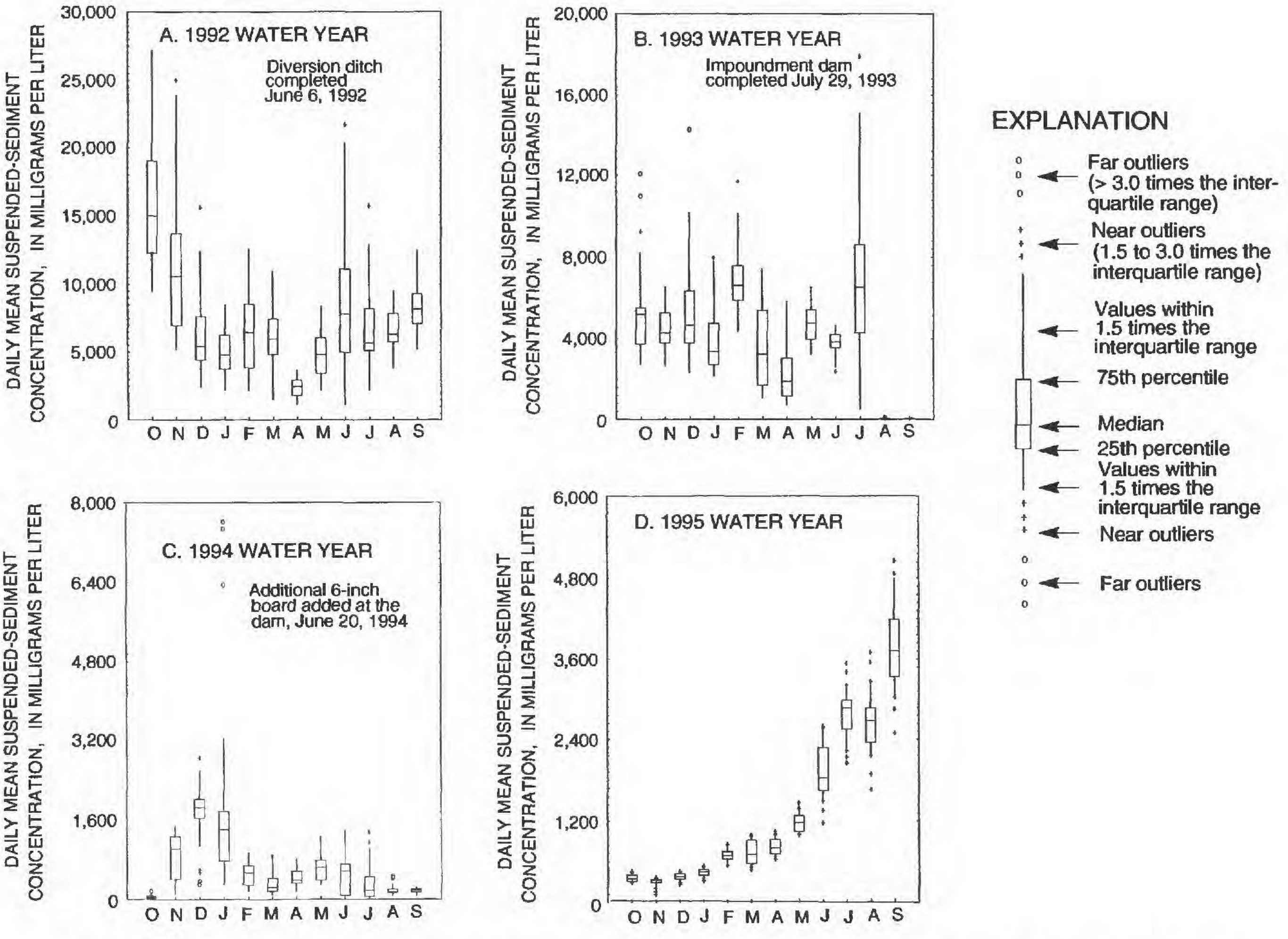


Figure 9. Distribution of daily mean suspended-sediment concentration in MDA outflow, by month, water years 1992-95.

The volume of sediment transported from the MDA to Onondaga Creek can be calculated if the suspended-sediment concentration and discharge at the outflow flume are known. Because sediment concentration is measured in the laboratory as mass per volume, it is converted to total volume through the mean specific gravity of the sediment particles (2.65) by the following formula;

$$V_s = C \times 0.0326 \times Q, \qquad (1)$$

where

V_s = sediment volume, in cubic feet per second per day;
C = daily mean sediment concentration, in milligrams per liter;
0.0326 = conversion factor; and
Q = daily mean stream flow, in cubic feet per second.

A total of 25,700 ft^3 (952 yd^3) of sediment was discharged from the MDA during March 1992, and the mean daily volume for 1992-95 was 6.6 yd^3. Mean daily volumes for water years 1992, 1993, 1994, and 1995 were 19.6, 4.8, 0.7, and 1.16 yd^3, respectively. Mean daily sediment concentration and mean daily sediment loads for Tributary 6, downstream from the MDA, in water years 1992-94 are published in USGS annual data reports for Western New York (U.S. Geological Survey, 1993, 1994, 1995, v. 3).

Particle-Size Analysis.–Suspended sediment samples from the MDA outflow were also periodically analyzed for particle size and sand split (percent finer than 0.062 mm). Results (table 4) indicate that the diversion of Tributary 6 had little effect; both before and after the diversion, 30 to 60 percent of the sediment consisted of clay-size particles (< 0.004 mm) and 80 to 100 percent was silt-size or smaller (< 0.062 mm). Sand size (> 0.062 mm) particles generally formed only a negligible percentage of the sample. After completion of the impoundment on July 29, 1993, however, from 50 to 80 percent of the sediment was clay sized, and from 95 to 100 percent was silt sized or smaller. These ratios do not represent the composition of sediment as it is discharged from the mudboils, however, because most of the sand-sized fraction settles out immediately and forms the volcanolike cone of the mud vent. Therefore, the sand component of the discharged sediment is much greater

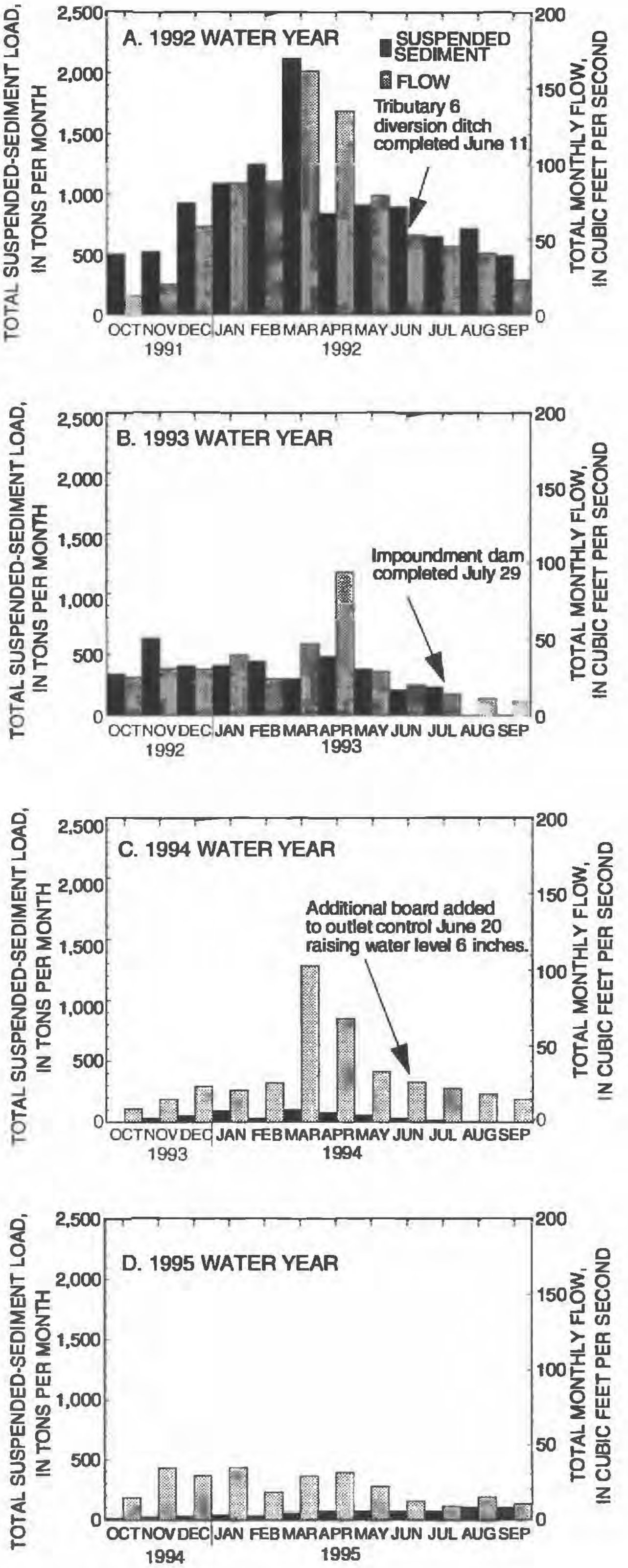


Figure 10. Total monthly sediment load and total monthly streamflow at mudboil/depression area outflow, water years 1992-95.

Table 4. Particle-size analysis of selected suspended-sediment samples from the outflow of the mudboil/depression area, Tully Valley, N.Y., 1991-95, showing percentage of particles less than specified diameter in sand-, silt-, and clay-size classes.

[mm, particle diameter, in millimeters; mg/L, milligrams per liter; --, no data]

		Particle diameter									
	Concentration	Clay		Silt				Sand			
Date	(mg/L)	0.002 mm	0.004 mm	0.008 mm	0.016 mm	0.031 mm	0.062 mm	0.125 mm	0.250 mm	0.500 mm	01.00 mm
1991											
Aug. 29	11,900	--	--	--	--	--	89	--	--	--	--
Sept. 04	13,100	--	--	--	--	--	96	--	--	--	--
1992											
Jan. 18	3,370	--	--	--	--	--	82	--	--	--	--
19	7,750	--	--	--	--	--	91	--	--	--	--
22	4,870	--	--	--	--	--	88	--	--	--	--
23	5,110	29	32	32	52	64	84	99	100	100	100
Feb. 07	11,000	40	45	61	73	87	96	99	100	100	100
11	9,230	--	--	--	--	--	96	--	--	--	--
14	13,100	--	--	--	--	--	95	--	--	--	--
Mar. 25	6,860	--	--	--	--	--	84	--	--	--	--
26	2,860	--	--	--	--	--	90	--	--	--	--
27	1,000	--	--	--	--	--	94	--	--	--	--
May 25	7,650	40	51	66	77	87	96	99	100	100	100
June 01	612	--	--	--	--	--	90	--	--	--	--
03	4,300	--	--	--	--	--	91	--	--	--	--
07	8,020	35	47	62	77	93	99	100	100	100	100
Nov. 23	3,360	--	--	--	--	--	85	--	--	--	--
1993											
Jan. 02	8,530	48	58	71	80	83	83	92	94	100	100
Mar. 30	1,750	30	37	47	57	67	79	93	99	100	--
30	1,000	--	--	--	--	--	98	--	--	--	--
Apr. 02	773	--	--	--	--	--	99	--	--	--	--
10	786	46	57	67	77	82	94	99	100	--	--
17	939	--	--	--	--	--	97	--	--	--	--
23	1,130	--	--	--	--	--	77	--	--	--	--
June 30	4,300	--	--	--	--	--	97	--	--	--	--
Aug. 03	47	--	--	--	--	--	100	--	--	--	--
06	20	--	--	--	--	--	93	--	--	--	--
Sept. 14	39	--	--	--	--	--	100	--	--	--	--
23	46	--	--	--	--	--	100	--	--	--	--
Oct. 02	54	--	--	--	--	--	97	--	--	--	--
1994											
Jan. 28	301	--	--	--	--	--	100	--	--	--	--
Feb. 06	645	--	--	--	--	--	100	--	--	--	--
16	807	--	66	--	--	–	99				
21	234	--	--	--	--	--	100	--	--	--	--
24	437	--	68	--	--	--	96	--	--	--	--
Mar. 22	468	--	83	--	--	--	100	--	--	--	--
23	483	--	--	--	--	--	100	--	--	--	--
24	307	--	48	--	--	--	88	--	--	--	--
27	498	--	--	--	--	--	100	--	--	--	--
Apr. 08	310	--	--	--	--	--	99	--	--	--	--
May 21	952	--	--	--	--	--	100	--	--	--	--
Nov. 11	194	--	--	--	--	--	99	--	--	--	--
1995											
Jan. 12	558	--	--	--	--	--	100	--	--	--	--
29	1,000	--	84	--	--	--	100	--	--	--	--
July 06	2,590	--	--	--	--	--	100	--	--	--	--
Sept. 03	3,710	--	--	--	--	--	100	--	--	--	--

than indicated in samples collected at the MDA outflow.

The increases in percentage of clay- and silt-sized particles after completion of the dam are a result of the increased settling time in the impoundment, during which the sand and larger silt-sized particles settled out. No correlation was found between sediment concentration and particle-size distribution.

Chemical Quality

Water samples were collected upstream and downstream of the MDA, as well from individual mudboils, for analysis for common ions, dissolved iron, and dissolved manganese. Physical characteristics such as temperature, pH, dissolved oxygen concentration, and specific conductance were measured onsite at the time of sample collection. Median concentrations of selected chemical constituents are given in table 5. Except for temperature, alkalinity, bicarbonate, and dissolved iron, median values for all constituents are substantially higher at the outflow of the MDA than at the inflow as a result of mudboil discharge from the underlying brackish-water aquifer. The higher median concentrations of most constituents in inflow and outflow for water years 1993-95 than for 1992 is a result of the diversion of flow from Tributary 6 in June 1992, which decreased the amount of dilution and resulted in higher concentrations of the chemical constituents. After the diversion, yearly median concentrations of most constituents remained fairly consistent. Results of the chemical analysis of individual samples collected upstream and downstream of the MDA are published in the USGS annual data reports (U.S. Geological Survey, 1993, 1994, and 1995, v. 3).

Ground Water

Mudboil discharge is driven by artesian pressure in the two unconsolidated, confined aquifers in the Tully Valley. The upper aquifer is recharged by

Table 5. Median values of selected constituents and physical properties at inflow and outflow of mudboil/depression area, Tully Valley, N.Y., water years 1992-95.

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter; --, no data collected at mudboil inflow during 1995 water year]

	1992		1993		1994		1995	
Constituent	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow*
Specific conductance (µS/cm)	454	3,310	590	5,960	562	6,400	--	4,720
Temperature (°C)	12.7	9.6	7.7	7.0	8.0	8.4	--	9.0
Calcium, dissolved (mg/L)	75	110	89.5	150	86.5	150	--	130
Magnesium, dissolved (mg/L)	14.5	42	18	74	17	69	--	59
Sodium, dissolved (mg/L)	6.95	520	8.4	980	9.3	950	--	770
Chloride, dissolved (mg/L)	12.5	820	13	1,700	14.5	1,750	--	1,650
Sulfate, dissolved (mg/L)	23	110	25	210	23.5	195	--	180
Alkalinity (mg/L)	230	176	249	172	258	180	--	184
Alkalinity, bicarbonate (mg/L)	281	215	304	212	314	220	--	224
Solids, dissolved (mg/L)	286	1,740	359	3,400	338	3,590	--	2,900
Iron, dissolved (mg/L)	13.5	10	13.5	10	17	20	--	15
Bromide, dissolved (mg/L)	.02	1.1	.02	2.5	.04	2.35	--	1.9

* limited sampling at mudboil outflow during 1995 water year

infiltration of precipitation that enters the unconsolidated deposits at the valley walls; the deeper aquifer is also recharged by precipitation, but this flow moves into the surrounding bedrock and discharges to the lower parts of the unconsolidated deposits that fill the valley. The points of discharge for these two aquifers are downgradient of the recharge areas and are at openings in the layers that confine these aquifers.

Freshwater Aquifer

Mudboils that discharge freshwater are within the Onondaga Creek corridor and on the south side of the MDA and are driven by artesian pressure within the upper aquifer. Increased recharge in the early spring and, to a lesser extent, in the fall of each year, causes increased artesian pressures that cause mudboils to discharge at increased rates. The increased discharge of water and sediment, in turn, causes increased subsidence at the land surface.

Recharge

The upper aquifer, which feeds the freshwater mudboils, is recharged from two areas—(1) the Tully (Valley Heads) Moraine at the south end of the valley and the valley walls south of the mudboil corridor, and (2) the alluvial fan at the mouth of Rattlesnake Gulf and, to a lesser extent, the alluvial fan at the mouth of Rainbow Creek. These areas of recharge, shown in geologic sections in figures 5 and 6, indicate that permeable deposits beneath the surficial lacustrine deposits are hydraulically connected to the Tully Moraine and to the alluvial fans at major side valleys and extend throughout the mudboil area and further to the north.

The alluvial fan at the mouth of Rattlesnake Gulf tributary valley consists of very coarse sand and gravel. Surface water in this side valley flows on bedrock until it reaches the upper edge of the alluvial fan, at an altitude of about 620 ft, and then infiltrates to the upper aquifer system. A series of discharge measurements taken at the contact between the alluvial fan and bedrock and at Tully Farms Road (about 1,400 ft downstream) in 1993 indicate that, during low-flow periods, the stream loses water to the unconsolidated deposits at a rate as high as 0.55 ft^3/s (nearly 250 gal/min). Discharge measurements on Rainbow Creek in 1993 indicate that the stream loses as much as 0.10 ft^3/s (45 gal/min) along a 1,200-ft reach. The contact between the alluvial fan and bedrock at Rainbow Creek is less distinct than at Rattlesnake Gulf—the last bedrock exposure is at an altitude of about 640 ft, and well logs from wells Od-400 and Od-456 (fig. 6) do not indicate as good a hydraulic connection with the upper aquifer system as at Rattlesnake Gulf.

Together, these recharge areas provide a nearly constant supply of water with sufficient hydraulic head to drive the discharge of freshwater from mudboils along Onondaga Creek and in the MDA (fig. 11). A preliminary mathematical model of the mudboil area was constructed to define the ground-water-flow regime and to predict the effect of depressurizing wells placed around the MDA (Daniel Bove, student, Cornell University, written commun., 1994). Results confirmed that flow from the Rattlesnake Gulf alluvial fan and the southern end of the Tully Valley are the predominant sources of water driving mudboil activity in this part of the valley, and that flow from the Rainbow Creek fan contributed only minimally to the freshwater aquifer.

Discharge

Discharge from the freshwater aquifer is primarily through the MDA, the Onondaga Creek mudboil corridor, and, probably, as northward underflow toward the northern end of the Tully Valley. Total calculated mudboil discharge from the MDA during this study ranged from 0.4 ft^3/s in fall to 0.9 ft^3/s in spring, and the volume discharged from mudboils within the mudboil corridor ranged from 0.01 ft^3/s to 0.3 ft^3/s; one of these mudboils, which flowed at a rate as high as 0.18 ft^3/s, caused the collapse of the Otisco Road bridge.

The quantity of water leaving the freshwater aquifer north of the mudboil corridor has not been quantified because the many springs along the valley walls near the northwestern end of the valley make the total discharge through this area difficult to estimate. Whether the upper mudboil aquifer is continuous is unknown, but remnants of a moraine have been found on the east valley wall, north of U.S. Route 20 (fig. 2) (Dr. Donald Pair, University of Dayton, Ohio, oral commun., 1995) and the discovery of a buried moraine on the west valley wall, as evidenced by recent drilling data collected between landslide areas LS-2 and LS-3 (fig. 2) (Sarah McCollough (student), Syracuse University, oral commun., 1995), may indicate the presence of a moraine, below the present valley floor, near the northern end of the Tully Valley. If such a feature is

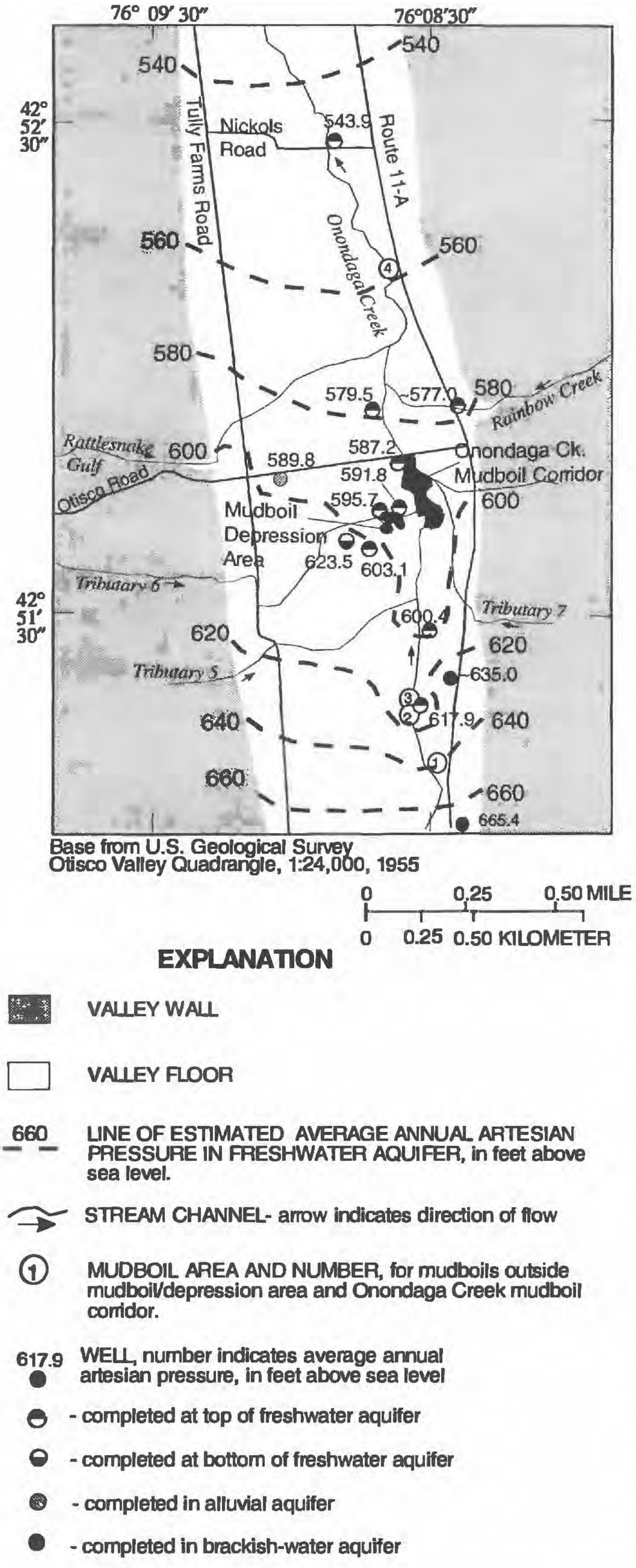


Figure 11. Estimated average annual artesian-head altitude in freshwater aquifer in central part of Tully Valley, N.Y.

present and is relatively impermeable, it likely forms the northern limit of the freshwater aquifer and explains the lack of numerous springs at the mouth of the Tully Valley, where it meets the West Branch Valley of Onondaga Creek, north of U.S. Route 20.

Chemical quality

Only a few water samples from the freshwater mudboil zone were collected for chemical analyses. Some were collected from within the MDA, and others at the MDA outlet, where freshwater and brackish-water mudboil discharges are mixed. Water samples were also collected from two wells near the MDA (well Od-405, 72 ft deep, just northwest of the MDA, and well Od-416, screened at a depth of 132-138 ft, just southwest of the MDA), and from three wells within the Onondaga corridor (depressurizing wells Od-450 and Od-451, both about 130 ft deep) along Otisco Road, and well Od-431 (74 ft deep, just west of Od-450). (Locations of wells are shown in fig. 3).

Specific conductance and concentrations of constituents such as dissolved chloride and sodium in samples from the freshwater aquifer (table 6A) were generally in the range found in surface-water samples collected (1) upstream from the MDA, (2) at the MDA inflow, (3) from the diversion ditch above the MDA, and (4) just upstream of the Onondaga Creek mudboil corridor (table 6B). The elevated specific conductance, chloride, and sodium concentrations in water from wells Od-450 and Od-451 and the 132-138 ft zone of well Od-416 (table 6B), which are all screened at the bottom of the freshwater aquifer, indicate possible seepage from the under lying brackish-water aquifer through the confining clay layer. Samples from Od-405 (finished in the top of the freshwater aquifer) did not have elevated concentrations. (Leakage from the underlying aquifer, close to the MDA is suspected—water from the brackish aquifer could move up into the base of the freshwater aquifer through a fracture in the clayey till and mix with the fresher water as it moves downgradient from the MDA, but the denser brackish water probably remains in the lower part of the freshwater aquifer. A detailed explanation of this mechanism is given in the following paragraphs.)

Table 6. Specific conductance and ion concentration in freshwater samples from selected sites in Tully Valley, N.Y., 1992-95.
[(NYSDEC), New York State Department of Environmental Conservation; USGS, U.S. Geological Survey; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter]

				Physical Property or Constitutent			
Sampling Location	Date	Collector	Specific conductance (µS/cm)	Chloride dissolved (mg/L)	Dissolved solids (mg/L)	Sodium dissolved (mg/L)	Sulfate dissolved (mg/L)
A. Mudboils and wells that tap freshwater aquifer in main mudboil/depression area							
MUDBOILS							
MB1[1]	03/10/92	(USGS)	464	430	215	47	57
	12/09/92	(NYSDEC)	398	37	284	47	17
MB7[2]	12/09/92	(NYSDEC)	504	62	370	55	16
	07/08/93	(NYSDEC)	453	54	284	51	16
WELLS (depths are in feet below land surface)							
number depth							
Od-405 (72)	08/05/92	(USGS)	517	73	286	76	29
Od-431 (68)	09/23/93	(NYSDEC)	381	49	231	55	22
Od-416 (138)	12/06/93	(NYSDEC)*	3,050	812	1,550	314	< 2
Od-450 (127)	01/11/94	(USGS)**	581	98	324	62	15
	03/24/94	(USGS)	766	150	406	73	14
	06/30/94	(USGS)	860	180	454	80	14
	09/07/94	(USGS)	840	190	463	84	13
	11/16/94	(USGS)	830	210	465	87	14
	03/01/95	(USGS)	860	220	460	90	13
	05/18/95	(USGS)	960	220	461	91	13
	08/17/95	(USGS)	990	230	481	95	14
Od-451 (123)	05/27/94	(USGS)	852	180	405	74	12
	09/07/94	(USGS)	847	180	453	75	10
	11/16/94	(USGS)	990	180	420	76	11
	03/01/95	(USGS)	809	190	405	74	9.6
	05/18/95	(USGS)	810	180	452	76	10
	08/17/95	(USGS)	845	180	401	78	11
B. Diversion ditch at Tully Farms Road and Onondaga Creek upstream of mudboil corridor							
Diversion ditch	07/21/92	(USGS)	429	7.3	235	5.3	17
	10/21/92	(USGS)	420	12	274	6.8	18
	01/20/93	(USGS)	406	6.7	242	5.7	20
	03/30/93	(USGS)	291	8.7	177	4.2	14
	04/02/93	(USGS)	269	8.0	174	2.9	12
Onondaga Creek	12/06/93	(NYSDEC)	561	53	322	45	28

[1] Turbid mudboil in southeast corner of mudboil/depression area.

[2] Mudboil adjacent to Otisco Road bridge.

*Sample collected from lower part of freshwater aquifer near mudboil/depression area where mudboils discharge brackish water.

**Sample may have been contaminated by freshwater used to develop the well.

Brackish-Water Aquifer

A dense clayey-till layer at an altitude of about 430 ft underlies the area of the Onondaga Creek mudboil corridor and the MDA between wells Od-450 and Od-451 at the Otisco Road bridge area and well Od-416 at the MDA (fig. 6). Water above this till layer is considered fresh (dissolved solids concentrations generally less than 500 mg/L), but water below this layer has much higher specific conductance and much higher concentrations of chloride and sodium, among other ions (table 7). For this reason, the brackish-water aquifer (brackish is defined in this report as salinity between 15 and 30 parts per thousand) is considered to be a separate aquifer. The dense clayey till (fig. 6), where it is continuous, may also act as a semipermeable confining layer through which the brackish, artesian-pressured water can only move upwards, slowly, leaving most of the chemical constituents below the clay layer.

Although the upper and lower aquifers differ in water chemistry, they appear to be hydraulically connected through the clayey-till layer in the MDA area because mudboils within the northwestern area of the MDA have a water-quality signature similar to that of the lower, brackish aquifer, as measured in the 298-ft-deep monitoring zone at well Od-416 (table 7). Water from one mudboil in the MDA, known as the salt mudboil, (MB2, table 7) is similar to that in the 298-ft deep zone, whereas water from the other

Table 7. Concentrations of selected chemical constituents in water samples from mudboils, sulfur springs, and wells tapping the brackish-water aquifer and water-bearing fractures in bedrock at Tully Valley, N.Y., water years 1992-94

[NYSDEC, New York State Department of Environmental Conservation; USGS, U.S. Geological Survey; ft, feet; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter]

			Physical Property or Constituent					
Sampling Interval	**Date**	**Collector**	**Specific conductance (µS/cm)**	**Chloride dissolved (mg/L)**	**Solids dissolved (mg/L)**	**Sodium dissolved (mg/L)**	**Sulfate dissolved (mg/L)**	**Calcium dissolved (mg/L)**
Mudboils[1]								
MB2	03/10/92	(USGS)	18,400	5,600	11,300	2,900	570	350
MB2	06/25/92	(USGS)	16,900	5,200	10,500	2,900	540	290
MB2	02/04/93	(NYSDEC)	25,900	7,099	6,760	4,040	863	378
MB2	09/23/93	(NYSDEC)	24,300	4,190	12,400	3,530	580	364
MB2	12/06/93	(NYSDEC)	24,300	5,730	11,800	3,520	761	363
MB3	12/09/92	(NYSDEC)	28,300	2,830	12,806	4,370	1,889	333
MB3	07/08/93	(NYSDEC)	3,300	695	1,830	344	73.1	125
Wells (depths, in parentheses, are in feet below land surface)								
Od-412	02/04/93	(NYSDEC)	10,800	2,640	2,800	1,570	452	220
Od-416 (298)	09/23/93	(NYSDEC)	21,000	5,370	10,700	3,030	633	409
Od-416 (462)	03/09/93	(NYSDEC)	116,000	28,500	57,500	19,000	2,890	1,470
Od-416 (517)	03/09/93	(NYSDEC)	56,100	13,600	27,700	8,430	1,840	920
Od-416 (608)	03/08/93	(NYSDEC)	196,000	43,600	98,400	33,000	4,140	2,120
Od-416 (633)	03/31/93	(NYSDEC)	340,000	67,500	169,000	59,200	3,170	2,340
Od-419 (40)	09/08/93	(USGS)	7,130	2,000	4,190	1,300	510	140
Od-419 (40)	12/06/93	(NYSDEC)	8,850	1,820	4,320	1,280	653	135
Springs[2]								
MS4	12/06/93	(NYDEC)	20,700	4,750	10,000	3,100	1,040	350
MS5	11/16/94	(USGS)	19,800	5,300	10,000	2,800	980	680

[1] MB2 Clear mudboil in southwest area of mudboil/depression area
MB3 Turbid mudboil in northwest area of mudboil/depression area

[2] MS4 Sulfur spring in backscarp of landslide LS-2
MS5 Sulfur spring in backscarp of landslide LS-4

mudboils in the northwestern area is a mixture of brackish water and freshwater. Surface geophysical techniques were applied, and the salt mudboil excavated, in an attempt to determine whether this mudboil was an abandoned well or just an older freshwater vent that was discharging brackish water through a fracture in the till layer, but no conclusive evidence was found. The gradual appearance of brackish water in discharge from mudboils was first noted by R. M. Waller (U.S. Geological Survey, written commun., 1993), who reported that the mudboils were discharging freshwater from the MDA in 1977, whereas his 1979 field notes indicate an increase in conductivity and salinity—possible evidence of the hydraulic connection between the two aquifers. Most of the mudboil discharge and subsidence during 1992-94 was centered around the northwestern area, which contained most of the brackish-water mudboils.

Recharge

The brackish-water aquifer is recharged from three main sources–the deep regional bedrock flow system, the Tully (Valley Heads) Moraine to the south, and the interconnected bedrock aquifers in the solution-mining collapse areas. Several sand and gravel zones that extend northward from the moraine to beneath the mudboil area and beyond provide recharge from the moraine, as evidenced by logs from several deep domestic wells in the southern part of the valley (Od-460 and Od-461) and the deep test-well site (Od-416), which indicate several permeable zones within the glacial sequence, as do data from a well drilled north of the mudboil area on Webster Road (Od-457). The most permeable zone, a basal gravel unit just above bedrock, has reported yields as high as 400 gal/min under flowing, artesian conditions. Before the solution-mining period, water in this basal unit probably entered the brackish aquifer through moraine deposits at the southern end of the valley and moved northward along the buried valley walls and floor in the weathered, fractured bedrock surface, and in the coarse-grained deposits just above bedrock. Infiltration at land surface provides only negligible recharge because it is limited by the fine-grained lacustrine unit and by the general upward ground-water gradient throughout the valley bottom that results from the 1,000-ft difference in altitude between the ridgetops and the present valley floor. This gradient is the source of artesian pressure in (1) some of the regional extensive bedding-plane fractures, (2) the weathered and fractured bedrock, and (3) the basal gravel system.

Expansion of salt-solution mining and the continued removal of the 150-ft thickness of salt may have altered the regional flow system. The collapse of large, unsupported brine cavities resulted in the fracturing and collapse in the overlying bedrock, and, as this process propagated upward, discrete bedding-plane "aquifers" in the bedrock became connected. In some places, fracturing and collapse features extended as far as up as the land surface, where they captured surface water and allowed it to enter the ground-water system.

In summary, the brackish-water aquifer receives recharge from several sources. Before solution mining, the main sources were natural recharge through the Tully Moraine and upward flow from the bedrock. Since the fracturing and collapse of bedrock beneath the solution-mining fields, additional recharge has been supplied by surface water and by water from discrete water-bearing zones within the bedrock that have been connected through the collapse process.

Discharge

Discharge from the brackish aquifer is from springs along Bare Mountain, both inside and away from landslide areas at the foot of the hillside, and from some mudboils in the MDA. Before solution-mining activities began, several brackish or salty springs discharged from the base of the valley wall at the foot of Bare Mountain and from two old landslide areas (landslide areas LS-1 and LS-2, fig. 2) northwest of Cardiff. These salty springs were the reason for the drilling of two Cardiff salt-exploration wells-Well 4 (Od-458) and Well 5 (Od-459) near Cardiff in the early 1880's.(See appendix 1.) Other salt springs could have been present in the valley, but none are documented.

The first report of a brackish discharge from mudboils in the MDA was made in 1979. Because no consistent water-quality data collection at individual mudboils or at the MDA outflow was begun until the fall of 1991, the greatest increase in salinity of discharge from the MDA is assumed to have begun when solution mining ceased in the late 1980's, when hydraulic heads increased to a new (postmining) equilibrium in the unconsolidated aquifers and bedrock. The salinity values measured in the 1992-95 study represent the highest concentrations discharged from the MDA to date.

The third location of discharge from the brackish-water aquifer apparently started just before or during the fall of 1992, when a "saltwater" spring at the southern end of what is now the Tully Valley landslide began to flow from a small subsidence area (Gary Miller, resident, oral commun., January 1993). A series of springs, both fresh and brackish, developed in the backscarp area just after the April 27, 1993 landslide, (LS-4 in figs. 2 and 12). The brackish springs are chemically similar to water from the 298-ft deep zone (well Od-416), the salt mudboil in the MDA, and springs along the foot of Bare Mountain, both inside and beyond the landslide areas (tables 7 and 8).

Chemical Quality

Chemical quality of the brackish-water aquifer is characterized here in terms of concentrations of selected chemical constituents in samples collected from (1) brackish-water mudboils in the MDA, (2) wells Od-412, Od-416, and Od-419, and (3) two brackish-water springs in landslide areas LS-2 and LS-4. Concentrations in mudboil discharge from the northwestern part of the MDA are in the range found in the brackish-water aquifer and are similar to those of a sample collected at the 298-ft zone of well Od-416 (table 7). Specific conductance of mudboil samples ranged from about 17,000 to 28,000 µS/cm,

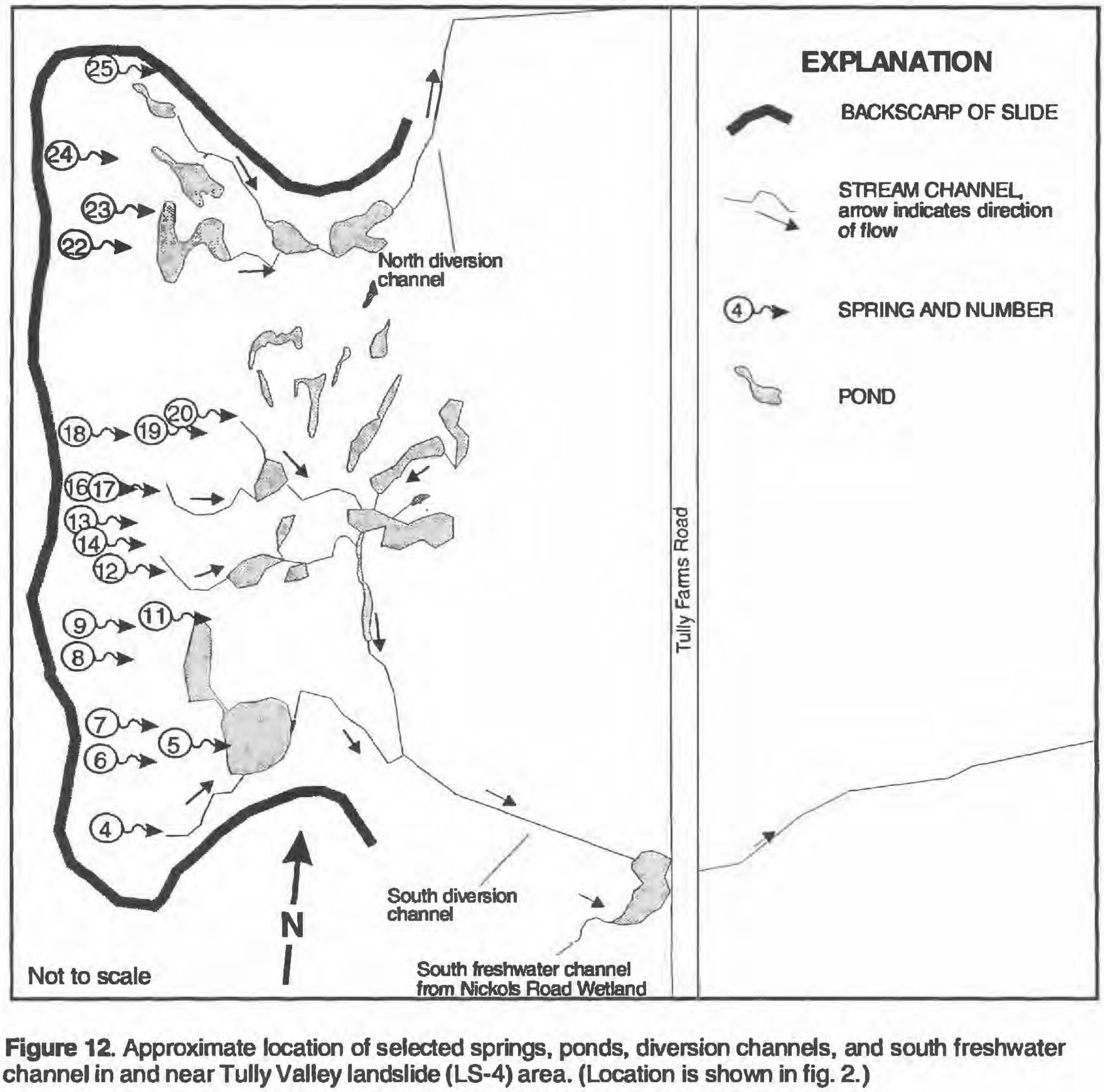


Figure 12. Approximate location of selected springs, ponds, diversion channels, and south freshwater channel in and near Tully Valley landslide (LS-4) area. (Location is shown in fig. 2.)

Table 8. Water-quality data from springs and streams draining the Tully Valley landslide (LS-4) area, May 1993 through July 1994.
[µs/cm; microsiemens per centimeter at 25 degrees Celsius, ppt; parts per thousand, °C; degrees Celsius, ft^3/s; cubic feet per second, ---; no data. Locations shown in fig. 12.]

Date and physical properties	Springs							South Freshwater channel	South Diversion channel	North Diversion channel
	4	5	8	17	20	22	25			
May 1993										
Specific conductance, in µs/cm	7,500	35,500	21,300	38,800	38,500	450	350	1,210	22,200	3,400
Salinity, in ppt	4.3	22.0	13.0	22.0	24.0	0.1	0.1	0.4	13.5	1.90
Temperature, in °C	13.6	13.8	10.5	10.3	11.0	16.0	11.5	11.4	12.3	14.1
Discharge, in ft^3/s	---	---	---	---	---	---	---	0.85	1.01	.126
August 1993										
Specific conductance, in µs/cm	737	25,700	26,000	48,800	33,400	462	500	2,170	25,200	4,610
Salinity, in ppt	0.2	15.7	15.6	31.4	20.7	0.1	0.1	0.75	15.1	2.5
Temperature, in °C	12.0	11.6	10.2	11.0	11.0	18.1	19.5	20.5	25.5	30.5
Discharge, in ft^3/s	---	---	---	---	---	---	---	.247	.522	.071
October 1993										
Specific conductance, in µs/cm	640	35,800	26,900	49,000	29,100	822	Dry	2,100	24,900	4,510
Salinity, in ppt	0.0	22.0	16.5	31.2	17.9	0.2	Dry	1.0	15.3	2.5
Temperature, in °C	9.4	10.6	10.3	10.4	10.9	10.5	Dry	14.3	19.1	19.4
Discharge, in ft^3/s	---	---	---	---	---	---	---	.137	.402	0.78
January 1994										
Specific conductance, in µs/cm	1,260	29,300	Dry	55,000	33,500	388	Frozen	1,690	27,900	5,400
Salinity, in ppt	0.3	18.0	Dry	35.0	20.6	0.0	Frozen	0.9	17.2	3.1
Temperature, in °C	5.0	10.0	Dry	9.2	10.3	1.8	Frozen	3.0	4.8	0.1
Discharge, in ft^3/s	---	---	---	---	---	---	---	.324	.478	0.97
April 1994										
Specific conductance, in µs/cm	355	31,900	9,790	31,000	32,700	388	374	776	18,500	2,290
Salinity, in ppt	0.0	19.7	5.7	19.3	20.1	0.0	0.0	0.2	11.1	1.3
Temperature, in °C	12.8	12.0	10.9	11.0	11.1	1.8	11.0	12.8	18.0	18.1
Discharge, in ft^3/s	---	---	---	---	---	---	---	2.29	1.21	.459
July 1994										
Specific cLonductance, in µs/cm	485	22,300	16,200	51,700	20,500	8,330	463	1,120	26,900	3,940
Salinity, in ppt	0.1	13.7	9.4	33.0	12.3	5.0	0.0	0.6	16.8	2.2
Temperature, in °C	10.6	12.9	11.1	11.4	12.0	11.9	27.5	15.1	19.3	23.0
Discharge, in ft^3/s	---	---	---	---	---	---	---	.433	.492	.144

and that of the well sample (Od-416) was 21,000 µS/cm. Chloride concentrations in the mudboil samples ranged from 2,800 to 7,100 mg/L, and those of the Od-416 well sample were about 5,400 mg/L, suggesting that the brackish aquifer is the source of flow. This aquifer also appears to be the source of flow from the two springs (MS-4 and MS-5) along Bare Mountain, inside landslide areas LS-2 and LS-4, respectively; here water from the brackish aquifer probably moves through the fractured, weathered bedrock to land surface. Water from the upper bedrock, at well Od-419 along the east valley wall, is similar to water at well Od-412, finished in the upper bedrock in the center of the valley near the MDA. Water in the deep bedrock (450 to 650 ft below land surface) at well Od-416 has significantly higher specific conductance and concentrations of chloride, dissolved solids, sodium, sulfate, and calcium (table 7) than any of the other water-bearing units; this, and its proximity to the underlying evaporite formations, indicate that it may be in hydraulic contact with those formations in the collapse areas in the brine field.

Although the data are insufficient for detailed analysis of the hydraulic interactions among the brackish-water aquifer, the water-bearing fractures in the bedrock, and brackish discharges from mudboils and springs in the Bare Mountain landslide areas, the water from the brackish-water aquifer can be categorized as a mixture of (1) chloride-enriched water flowing northward from the southern part of the Tully Valley, and (2) discharge from water-bearing fractures in the bedrock that crop out along the valley walls. The water is further modified as it passes through, and mixes with, water from the freshwater aquifer before discharging through mudboil vents in the northwestern part of the MDA.

The brackish water from certain springs in the Tully Valley landslide area has higher chemical concentrations than the discharge from the most brackish mudboils in the MDA. The landslide springs are adjacent to the Bare Mountain valley wall and to water-bearing zones within the bedrock. These water-bearing zones, which rise to the north at about 50 ft/mi, are probably fed by chloride-enriched waters from the collapse-zone areas, but not necessarily from the solution-mined cavities in the brine field. This water then discharges through springs in the backscarp area of the slide with limited dilution from the unconsolidated freshwater aquifer. This shortened pathway allows only minimal dilution during most of the year. More data from the recharge areas that feed the brackish-water aquifer and discharge points from this aquifer would be needed to adequately describe this flow system—a project beyond the scope of this study.

Land Subsidence and Landslides

Several forms of land subsidence have occurred in the Tully Valley over the past century, and landslides have occurred along Bare Mountain as long ago as the Late Pleistocene –14,000 years BP (before present) (Jäger and Wieczorek, 1994). Recent human-induced subsidence from salt-solution mining is fairly well documented, but most landslides and other forms of land subsidence are not. Subsidence due to mudboil activity has disrupted public utilities and destroyed the Otisco Road bridge over Onondaga Creek, and the 1993 Tully Valley landslide destroyed three houses and temporarily closed a section of Tully Farms Road. These and similar events, and their possible causes are discussed in the following paragraphs.

Subsidence from Salt-Solution Mining

Salt-solution mining in the southern Tully Valley began in 1889 and ceased in 1988. The nearly 100 years of salt solution-mining removed about 100 million tons, or 31,000 acre-ft of salt (Walker and Mahoney, 1993). Initial solution mining took place in the upper (F4) saltbed (figs. 4 and 5) and removed most of the 35- to 45-ft-thick salt layer at 31 wells in the east brinefield area. Early and frequent caving within the solution-mined cavities was documented (Larkin, 1950), but no general surface subsidence was noted, and no surface-subsidence measurements were made in either brinefield area until the late 1950's. From 1895 through 1900, 21 solution wells were drilled in the western brinefield area and resulted in similar caving (Larkin, 1950). As more wells were drilled into the deeper salt beds, other well-development and pumping strategies were tried in an attempt to decrease the caving and increase brine production.

By 1950, a total of 99 wells had been drilled in the eastern and western areas, 86 of which were abandoned as a result of caving, shearing of well casings, and collapse of the overlying bedrock into solution-mined salt cavities. Bulking of roof debris—that is, the collapse of roof materials onto the cavity floor, quickly filled the cavity with rock rubble and brought the collapse to a halt before the cavity could propagate higher into the bedrock or reach land surface. Fernandez (1992) stated that such bulking might, in the long term, lead to a broad, small-scale subsidence that would not be noticeable at the land surface.

As solution-mining activities continued in the 1930's, additional wells were drilled into the deeper saltbeds, and more aggressive solutioning techniques were used to increase the quantities of brine (Larkin, 1950). As the volume of salt extracted from a few production wells increased, a form of land subsidence began to occur in the 1940's wherein the debris pile did not build up to the roof to prevent further caving, rather, the collapse propagated to land surface, forming a "chimney" or rock-filled cylinder. Both types of collapse (bulking and chimney) continued into the early 1980's (Walker and Mahoney, 1993).

General land subsidence and development of rock fissures along the eastern side of the east brine field area were noted as early as 1943 (Larkin, 1950), and the subsequent development of several chimney-collapse areas prompted land-subsidence surveys in both brine field areas in the late 1950's. The extent of land subsidence due to the removal of salt since 1957, when the initial survey was made, is depicted in figure 13. (The subsidence measurements in the east field began after closure of this field and, thus, may not portray the total extent of subsidence.) This map indicates subsidence of 5 ft to more than 50 ft in the two brine-field areas and along a proposed east-west bedrock structure (Haley & Aldrich of New York, 1991) that apparently intersects the two brine-field areas. Although subsidence outside the brine field has not been documented, local landowners have noted bedrock fracturing upslope of the east brinefield area.

Subsidence from Discharge of Mudboil Sediments

The discharge of turbid water and sediment from mudboils has been documented since 1899. The Syracuse Post Standard article of October 19, 1899 states "the nearby bluff is slowly sinking," indicating land subsidence while this mudboil was active. This description, and recent measurements of subsidence at the MDA and along Otisco Road near the collapsed bridge, indicate that the removal of fine-grained sediment at depth can cause slumping and collapse in the overlying confining silty-clay unit. As the volume of material removed increases, the overlying material can no longer support its own weight, and the land surface slowly subsides to replace the materials removed at depth. Large blocks of earth have slumped and created a stepped landscape at the MDA, where vertical subsidence ranges from 15 to 20 ft.

The pattern or direction of subsidence has not been steady nor consistent. Mudboil activity, as interpreted from aerial photographs, has occurred in the eastern, southwestern, and northwestern parts of the MDA (fig. 14C). Subsidence was occurring in the southwestern area in the early 1970's, and local landowners report mudboil activity in the eastern area as early as the 1950's. Before that, mudboil activity was apparently a sporadic and seasonal event. By 1978 (fig. 14B), two areas of mudboil discharge were visible in aerial photographs, and land subsidence was extending southward and eastward and; by the mid-1980's, the area of activity had begun to widen (fig. 14C).

The eastern area is generally quiescent except for a mud vent on the south side, adjacent to the abandoned petroleum pipeline (MB-1, fig. 14D). In 1991 this vent was about 10 ft in diameter and over 20 ft deep. In the spring of 1992 it became active and discharged a large volume of water and sediment into the wetland area, and the nearby hillside slowly subsided. By the spring of 1993, however, discharge from this vent had slowed, as had the subsidence, although a small discharge of sediment and water continued. Most discharge from the eastern area is freshwater, but at least one vent within the eastern wetland discharges a clear, but brackish, flow that enters the MDA-outlet channel just above the old buried pipeline. The actual location of the brackish vent(s) has not been found.

New mudboil activity began in the northwestern area in 1991 (fig. 14D) and formed a semicircular pattern that was migrating northwestward. In July 1994, a mudboil became established on the east side of the southwestern area and, in early 1995, caused land subsidence of as much as 2 ft per month within a 100-ft radius of the vent. Mudboil vents on the southern side of the southwest area discharge freshwater, but one brackish-water mudboil vent (MB-2, fig.14D)

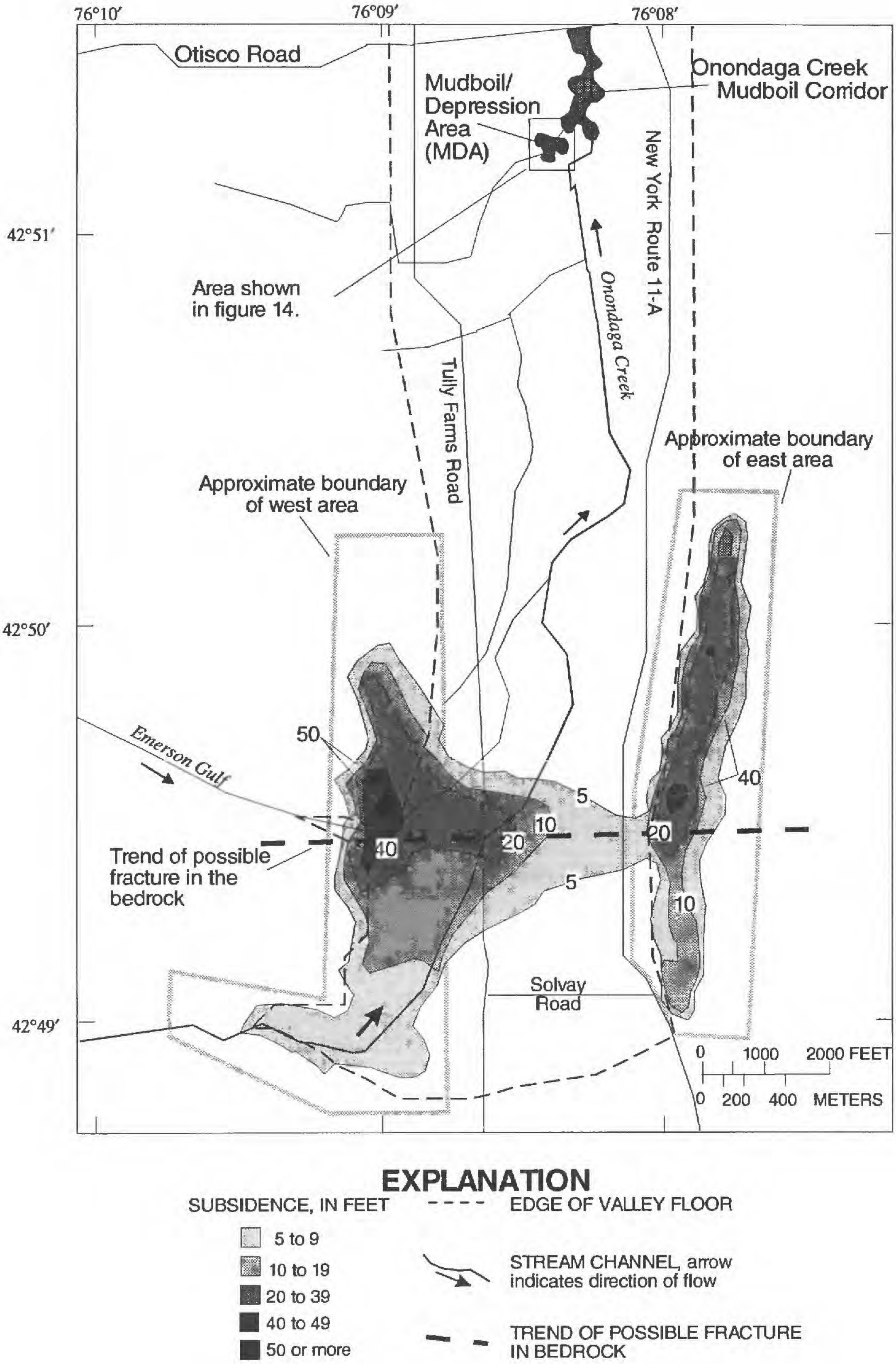


Figure 13. Extent and depth of brinefield subsidence (1957-93) in east and west areas and along a possible bedrock fracture in southern part of Tully Valley. (Modified from Walker and Mahoney, 1993, fig. 7. Location is shown in fig. 2.).

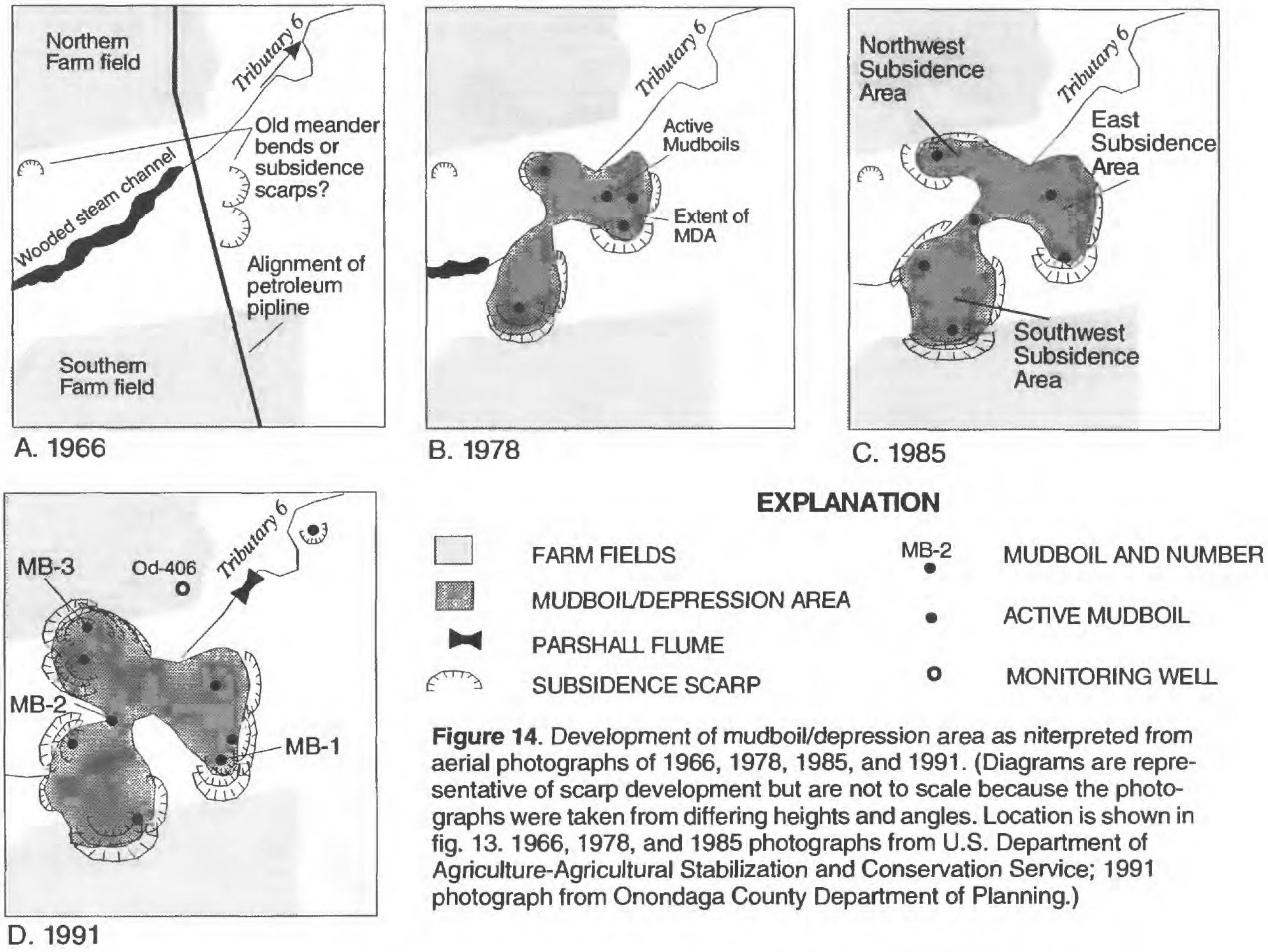


Figure 14. Development of mudboil/depression area as niterpreted from aerial photographs of 1966, 1978, 1985, and 1991. (Diagrams are representative of scarp development but are not to scale because the photographs were taken from differing heights and angles. Location is shown in fig. 13. 1966, 1978, and 1985 photographs from U.S. Department of Agriculture-Agricultural Stabilization and Conservation Service; 1991 photograph from Onondaga County Department of Planning.)

continuously discharges on the northern side of this area. In late 1995, most mudboil activity and land subsidence was along the south side of the southwestern area. Land subsidence in the northwestern area appears to have slowed in late 1994.

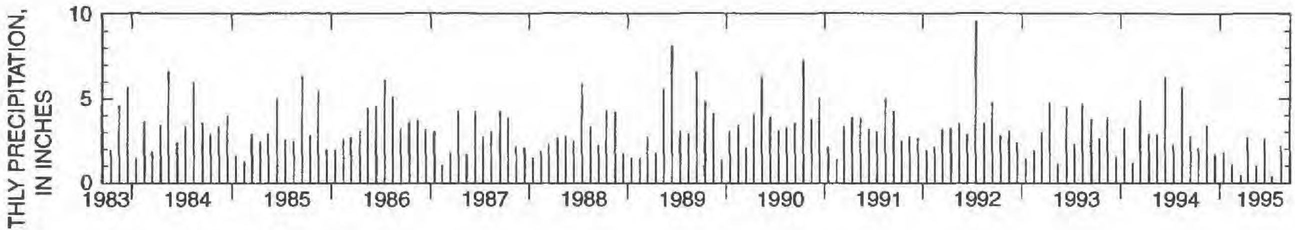
Subsidence from Dewatering of Fine-grained Deposits

Land-surface subsidence can also result from the removal of water from finer grained sediments. Early operations in the brinefield had injected "excessive amounts of water" from the Tully Lakes (Larkin, 1950, p. 3) to dissolve the salt and lift the saturated brine from the wells to the land surface. Operations were soon changed to use of an air-lift system to make the wells flow, but additional water was needed to keep the brine levels near the top of the casings. The loss of water through underground leakage, described by Larkin (1950), indicates either that extensive bedrock fractures were present in the brine field, and(or) that water was escaping into the coarser grained glacial deposits. Larkin also noted that, in the western brinefield area, a "water vein" (probably within the Rondout Formation, fig. 4) was used to dissolve the salt in several clusters of wells in the mid 1930's. This freshwater was usually "cased off" but was used in the production of saturated brine throughout the production period in the western field area. In the late 1930's, well casings in other well clusters on both sides of the valley were pulled to add this volume of water to that which was injected from the Tully Lakes for salt-solution mining.

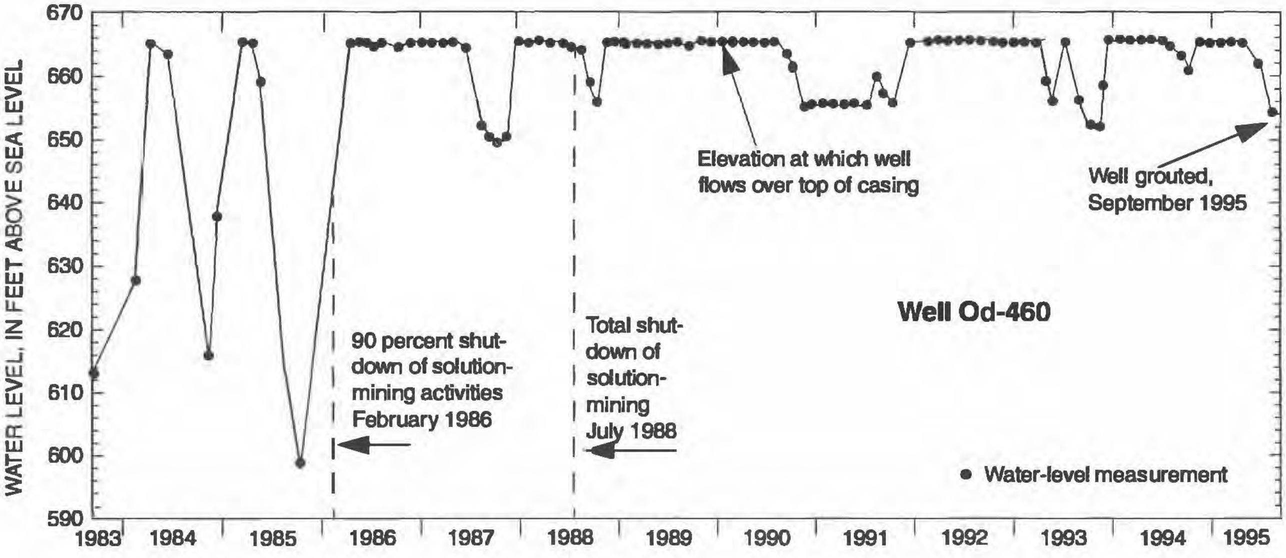
Beginning in the 1960's, the solution-mining company no longer needed surface water from the Tully Lakes to produce brine from the salt layers because the hydraulic connection between the salt beds, the overlying collapsed and fractured bedrock, and the unconsolidated deposits provided sufficient water for the process. The practice of removing casings from the wells to allow entry of ground water from specific bedrock water-bearing zones further increased the amount of water available for salt dissolution; thus, withdrawal of more than 1 billion (10^9) gallons of saturated brine annually was feasible without the injection of surface water into the solution cavities.

The effect of this method on the Tully Valley aquifers is unknown. Water-level information is limited because most domestic water supplies were from springs or shallow wells along the valley walls. Water wells had been drilled for company-owned homes in 1979, and subsequent water-level measurements (1983-95) provided the first opportunity to detect a connection between the brine fields and the deep coarse-grained unconsolidated deposits in the southern part of the valley. Water-level fluctuations in well Od-460 (fig. 2), a 400-ft deep well completed in a basal sand and gravel aquifer on the east side of the Tully Valley, are plotted in figure 15. Water levels in the well during the summer and fall of 1983-85 fluctuated by as much as 70 ft in response to brine withdrawals from the salt-solution cavities in the western brine area. (The eastern brine area was closed by 1959.) Water-level fluctuations after the 90-percent reduction in brine production were only about 10 ft. This well has flowed at land surface during the greater part of each year since 1986 and ceases to flow only during the driest summer months.

The water-level declines and recovery noted in well Od-460 probably reflect the aquifers' response to withdrawal from, and recharge to, the coarse-grained unconsolidated deposits of the Tully Valley. The large water-level declines can cause slow compaction of the fine-grained deposits because the draining of the underlying coarse-grained materials lowers the hydrostatic pressure within these deposits. Thus, as the fine-grained deposits drain, they become compacted by the weight of the overly-



A. PRECIPITATION



B. WATER LEVELS

Figure 15. (A) Monthly recorded precipitation at the Syracuse, N.Y., airport (1993-95), and (B) water levels in well Od-460 showing decreased fluctuations after 90-percent reduction in salt-solution mining activities in 1986 in western brine field area. (Maximum water level is undetermined. Well location is shown in fig. 2.)

ing deposits. This type of compaction can cause widespread land-surface subsidence; a detailed description of the process can be found in Lofgren (1961), Bull (1964), Poland and others (1975), and Ireland and others (1984).

A series of aerial photographs were taken in May 1993, and a relief map of the valley floor (5-ft contours) was produced to assess the possibility of valleywide subsidence resulting from dewatering. This map was overlain on the Otisco Valley 7.5-minute Quadrangle (1955), which has 20-ft contours. The areas of solution-mining subsidence (fig. 13) were clearly recognizable, but whether small-scale subsidence had occurred north of this area in response to aquifer dewatering during the last 25 years of solution-mining operations could not be determined.

This subsidence process stopped soon after the cessation of major ground-water withdrawals in 1986 because pore-water pressures in the coarse-grained unit quickly recovered. The water-level fluctuations in well Od-460 (fig. 15) clearly show that ground-water levels that previously fluctuated as much as 70 ft have returned to a seasonal fluctuation of 5 to 15 ft.

Tully Valley Landslide

The largest landslide in New York State in the past 75 years (Fickies, 1993) occurred on April 27, 1993, at the foot of Bare Mountain on a gently sloping hillside (slope about 10 percent), about 1 mi north of Otisco Road (LS-4, fig. 2). This earth-slump and mudflow landslide flowed about 2,500 ft onto the valley floor. No injuries occurred, but three houses were destroyed, 1,200 ft of Tully Farms Road was buried beneath 12 to 15 ft of mud and soil debris, and nearly 1 Mgal/d of water drained into the backscarp area (fig. 12). A group of local, State, and Federal agencies quickly responded and, within hours, had begun remediation activities to drain the backscarp area and stabilize the slide mass.

The hillside stratigraphy was clearly exposed within the backscarp area. The lowest exposed unit was a massive red, silty-clay unit, probably similar to the massive confining layer found at the mudboil area. Above this unit was a partly saturated 45-ft-thick glacial sand and gravel unit capped by a 3-ft-thick layer of lacustrine clay, silt, and fine sand. The surficial deposit was a mixed colluvial and glacial sand and gravel about 15 ft thick that was saturated at its base.

Several questions concerning the stability of Bare Mountain after the landslide were raised in discussions with local residents. They stated that, before the slide, the foundation of one house recently required repair because the cellar wall facing Bare Mountain was bulging inward. Several residents indicated that the land surface of a small wetland, west of Tully Farms Road, was slowly rising and falling. Finally, in 1990, the New York State Department of Environmental Conservation investigated subsidence features in relation to solution-mining activities in the southern part of the Tully Valley. A local farmer called attention to a small area of subsidence in what was to become the southern end of the Tully Valley landslide. The officials noted:

> The land had dropped exposing a scarp in two "steps" that totaled roughly 5 to 6 ft in height. At the base of the scarp is a graben that curves toward the northeast. The downhill scarp of the graben is lower than the uphill one. Both the slumped area and the graben had numerous small cracks.
>
> (Laura Snell, New York State Department of Environmental Conservation, Division of Mineral Resources, written commun., 1990).

Discussions with a local landowner in January 1993 revealed that this subsidence area had become larger and was discharging "salty" water that had killed some vegetation during the fall of 1992 (Gary Miller, local resident, oral commun., 1993).

Even though the above information indicates that the slope that failed was showing signs of instability several years before the landslide, several other factors contributed: (1) The east-facing slope of Bare Mountain, from Route 20 south to Otisco Road, has a much different topographic character than other slopes in the Tully Valley and is less steep as it approaches the valley floor; (2) the middle and upper slopes above the slide area did not have the deeply cut stream channels that are incised down to bedrock on slopes elsewhere in the Tully Valley; (3) the colluvial deposits of this slope allow greater water storage than on other slopes in the valley, where water can freely drain to the incised stream channels and flow quickly to valley floor; (4) the blizzard of March 1993, followed by 7.5 in. of rain in April 1993, supplied greater-than-average amounts of water to the Bare Mountain hillside; and (5) evapotranspiration was minimal because the trees had not yet "leafed-out". Thus, the additional water stored in the fractured bedrock and colluvial materials could have acted as a hydraulic piston that was the final step in initiating the slide.

The upper part of the east-facing Bare Mountain slope also differs from other ridges in the region in that it is capped by the Tully Limestone. Near the crest of the ridge is a sheer 25- to 30-ft wall of Tully Limestone that extends more than 1,500 ft parallel to the ridge. Below this wall are several sheer wall exposures of upper Hamilton Group Shales (Ludlowville Formation) that extend for several tens to hundreds of feet, parallel to the ridge (Dr. William Goodman, University of Rochester, and Dr. Herman Muskatt, Utica College, oral commun., 1994). The most prominent feature on the upper hillside is a secondary ridge that is parallel to the upper ridge and contains a northward dipping valley known locally as the "Grand Canal." This valley intersects another southward-dipping valley several hundred feet above the landslide area. No sign of flowing water is evident in these valleys, although a closed depression at their juncture may hold some water in the spring and possibly during extremely wet periods. Downslope from this closed depression is a broad swale that extends down to the landslide area but shows no indication of flowing water. Similar side-slope features can be found along other parts of the Bare Mountain–some dip to the north and others dip to the south, and their intersection form a closed depression with a swale below. Further north along the slope, the "wall and canal" features persist but diminish in size. These features possibly concentrate ground-water flow from the upper slope and channel it down to the colluvial gravel and clay contact at the midpoint of each landslide area.

Soon after the April 27, 1993 landslide, a series of springs discharging from two different sources developed in the backscarp area (fig. 12). Freshwater springs generally discharged from the base of the lower gravel unit through the summer of 1993, while discharge from the upper gravel unit stopped flowing a few days after the slide. Brackish-water springs, containing notably high amounts of hydrogen sulfide and methane, discharged from either the bedrock or from beneath the massive red silty-clay unit. Several of these springs discharged from the floor of the backscarp and readily migrated upslope toward the base of the backscarp. Initially a few of these springs discharged fine sand, silt, and clay, but as the flow decreased, the discharge of sediment ceased. A sediment-laden discharge returned during the spring of 1994 but ceased soon thereafter–similar to the seasonal mudboil discharges reported along Onondaga Creek from the late 1800's through the 1960's.

Few data have been collected at the Tully Valley landslide area (LS-4). Monthly flow and water-quality measurements, including temperature, specific conductance, and salinity, were collected from selected springs and stream locations for 1 year after the slide. The data indicated that, during the summer and fall, freshwater discharge from the gravel units decreased, and the salinity and conductivity of the bedrock-derived brackish springs increased (table 8)–probably because less freshwater was available to provide dilution. The number of springs also varied as springs migrated within the backscarp area. During spring of 1994, for example, the number of springs sharply increased as snowmelt and rain recharged the Bare Mountain hillside. Total discharge of and chemical quality of water in the summer of 1994 were similar to those of the summer of 1993, indicating a stable rate of discharge from bedrock-derived springs in the backscarp area.

Other Landslides in the Tully Valley

During the investigation of the Tully Valley landslide, another, older landslide (LS-3, fig. 2) was discovered several hundred feet north of the 1993 slide. The size of the backscarp area, the slope of the scarp, and the number of freshwater springs within the older landslide area were similar to those of the Tully Valley slide. Local historical records were checked, but no mention of a landslide was found in the 200-year history of the town of LaFayette. Inspection of the hillside north of these slides revealed other slides (LS-1 and LS-2, fig. 2) in a geologic setting similar to that of the Tully Valley slide. The two northernmost slides have both fresh- and brackish-water springs, and the land features are similar to those in the two other slide areas.

After the Tully Valley landslide, Jäger and Wieczorek (1994) completed a photo inventory and field examination of landslides in the Tully Valley and the adjacent Otisco and Butternut Creek Valleys, just west and east of the Tully Valley, respectively. They found that most of the recent landslides were smaller than the Tully Valley landslide, and the larger slides were caused by extreme hydrologic events. The ancient landslides–those that occurred soon after the last glacial recession–were triggered by rapidly falling proglacial lake levels or by extreme climatic events during that time. Human-induced activities, such as slope modification, have also resulted in small, recent landslides in conjunction with seasonal rainfall and snowmelt periods.

The only other large, documented landslide in the Tully Valley was apparently manmade. A massive landslide occurred within the Tully gravel pit, on the west side of the Tully Moraine, in 1921, when the oversteepened slope within the pit failed, and several workers were injured or killed (appendix 1). Local residents indicated that smaller slides have occurred in the valley, including several during the spring of 1993, but nothing of the magnitude of the four landslides on the east-facing Bare Mountain hillside (fig. 2).

MUDBOILS

Results of the data-collection efforts in the Tully Valley indicate three distinct aquifers in the unconsolidated deposits in the Tully Valley near the mudboils—a surficial unconfined aquifer derived from the alluvial fans of Rattlesnake Gulf and Rainbow Creek, an underlying confined freshwater aquifer, and a confined brackish-water aquifer. Water levels in the surficial aquifer fluctuate about 10 ft, on an annual basis, in wells distant from Onondaga Creek, whereas water levels in wells near the creek fluctuate less than 3 ft. The direction of flow in the surficial aquifer is from the valley walls toward Onondaga Creek. The seasonal water-level fluctuations in response to recharge and discharge are typical for valley-fill alluvial deposits.

Water-level fluctuations and water-table gradient in the confined freshwater aquifer differ from those in the surficial aquifer. The fluctuations in the freshwater confined aquifer are generally around 5 ft, and gradients are generally downvalley (fig. 11). Pressure fluctuation in this confined system is about the same everywhere.

The brackish-water aquifer cannot be characterized because data are limited, but water-level measurements in well Od-416 (screened at 298-ft depth) indicate patterns similar to those in the upper confined aquifer. This generalized description of the hydraulic characteristics of each aquifer formed the basis for initial remediation activities that, in turn, furthered the understanding of the conditions that created the mudboils and why they persist.

Initial Remediation Efforts

The Onondaga Lake Management Conference used the initial data collected in this study to identify and develop remediation strategies to decrease sediment discharges and land subsidence in the mudboil areas. Several remediation activities that were initially identified were eliminated as being infeasible or too costly. The first project chosen for implementation was designed to reduce the surface-water contributing area to the MDA by diverting Tributary 6, as explained previously; the second entailed the construction of an impoundment dam at the MDA outlet to decrease the amount of sediment discharging to Onondaga Creek; and the third project entailed installation of wells to reduce artesian pressure near the Otisco Road bridge in an attempt to slow land subsidence by allowing the artesian-pressured water to flow without entraining sediment. The results of these projects are to be used to determine future remedial efforts in the Tully Valley.

Surface-water Diversion

An assessment made by the U. S. Army Corps of Engineers (1992) indicated that diverting flow from the upper part of the MDA watershed (west of Tully Farms Road, fig. 3) would decrease stormflow and spring runoff entering the MDA and thereby reduce sediment discharge from the MDA to Onondaga Creek. On June 11, 1992, flow from the upper 0.7 mi^2 of Onondaga Creek Tributary 6 watershed was diverted to Tributary 5 (the next drainage to the south of the MDA); the changes in flow that resulted from this diversion are shown in figure 16A. Monthly inflows to the MDA during the spring of 1992, before the diversion, were as high as 4 ft^3/s, and the peak spring flows thereafter (1993-95) were only half this value. More important, the duration of high flows was substantially reduced. Total inflow values to the MDA for water years 1993-95 were about one-third the 1992 value.

The total discharge from MDA mudboils—that is, the discharge leaving the MDA minus the discharge entering the MDA is shown in fig. 16B and table 9. The mudboil discharge responds to seasonal precipitation, but not immediately to large amounts

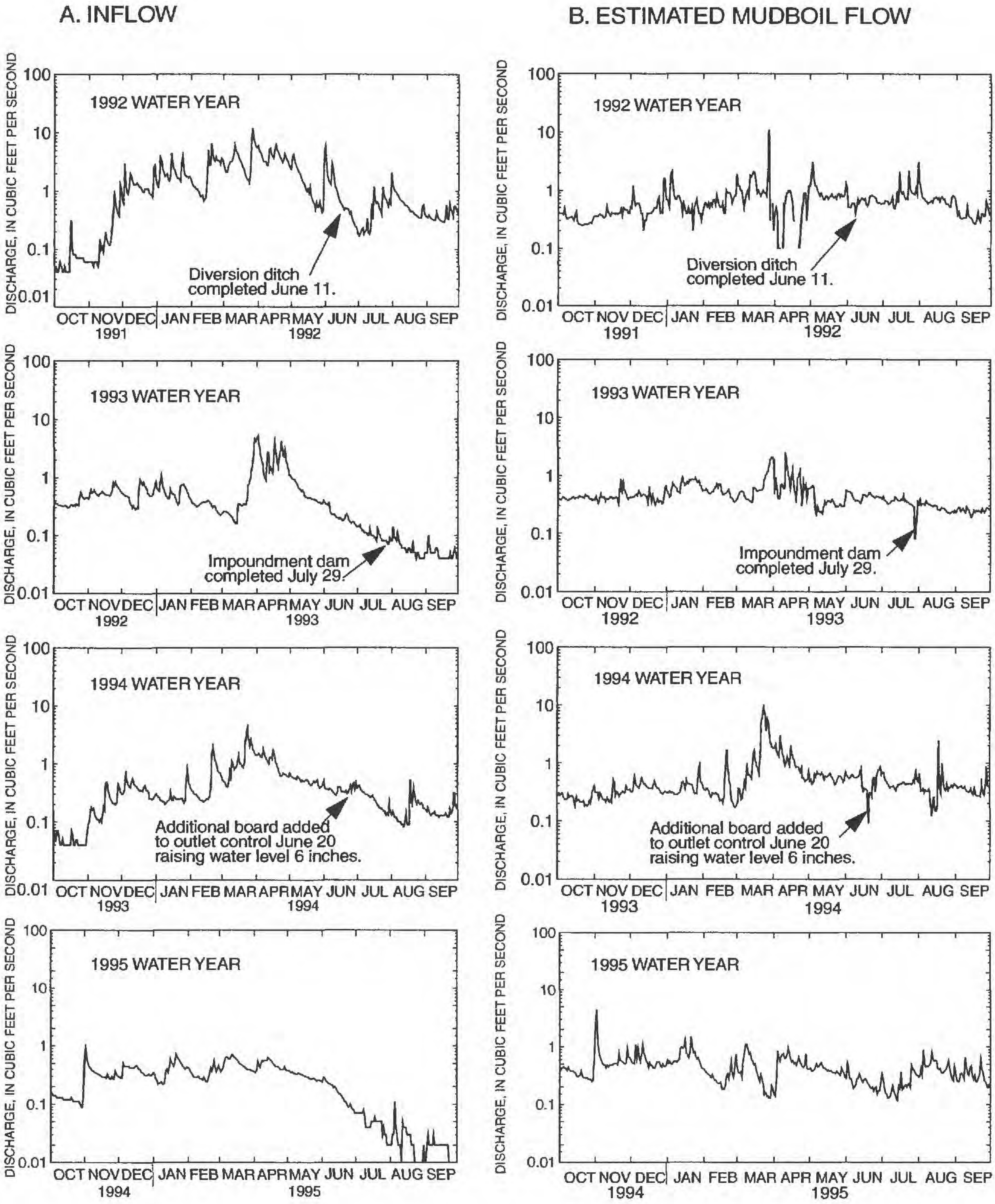


Figure 16. Hydrographs of daily mean flow into and estimated mudboil flow out of mudboil/depression area (MDA) , water years 1992-95. A. Measured inflow. B. Estimated mudboil flow, calculated as outflow from MDA minus inflow to the MDA.

of precipitation, indicating that the mudboils are fed by a fairly shallow but expansive flow system.

Annual runoff in most of New York State normally accounts for 60 to 70 percent of the annual precipitation. Annual runoff from Tributary 6 *above* the MDA was 67, 88, 58, and 54 percent of annual precipitation, respectively, for the 1992-95 water years, whereas annual runoff from Tributary 6 *below* the MDA for these years represented 93, 135, 114, and 119 percent of annual precipitation, respectively. This indicates that the water discharging from the MDA mudboils is from a source much larger than the drainage area of the MDA and the upstream tributary area.

As discussed earlier, sediment concentration at the MDA outflow is highest when the flow is lowest because the mudboil area acts as a point source for sediment discharge. High flows, by contrast, consist mostly of water entering the MDA with a low sediment concentration that dilutes the sediment discharging from mudboils through which Tributary 6 flows. This inverse sediment-to-discharge relation was not constant during the study period—even though the slope of the relation before the Tributary 6 diversion (fig. 17A) is similar to the slope after the diversion (fig. 17B) the distribution of data before the diversion was more uniform throughout the range of flow. Data collected after the diversion (fig. 17B), tend to be clustered in the low range of flow because the high flows were diverted. Concentrations for a given flow decreased slightly after the diversion, probably more as a result of decreased mudboil activity than from a decrease in flow. Median sediment concentration after the diversion (5,215 mg/L) differed little from that before the diversion (5,570 mg/L), indicating that the main benefit of the diversion was the decrease in high flows and associated sediment loading from the MDA to Onondaga Creek.

Table 9. Annual discharge, runoff, and precipitation statistics for Tributary 6 watershed areas upstream and downstream of mudboil/depression area, Tully Valley, N.Y., water year 1992-95, and corresponding derived statistics for the mudboil/depression area.

[ft^3/s; cubic feet per second; (ft^3/s)/ mi^2, cubic feet per second per square mile. Locations shown in fig. 3.]

	Water Year †			
Location	1992	1993	1994	1995
Watershed area upstream of mudboil/depression area, in mi^2	**0.96 ††**	**0.25**	**0.25**	**0.25**
Total discharge, in ft^3/s	556.	197.	159.	95.
Annual mean discharge, in ft^3/s	1.52	0.54	0.44	.26
Annual runoff, in (ft^3/s)/ mi^2	2.01	2.07	1.67	1.00
Annual runoff, in inches	27.3	28.2	22.7	13.6
Precipitation, in inches	40.7	32.0	38.8	25.4
Ratio of annual runoff to annual precipitation	.67	.88	.58	.54
Watershed area downstream of mudboil/depression area, in mi^2	**1.02††**	**0.32**	**0.32**	**0.32**
Total discharge, in ft^3/s	804.	372.	380.	261.
Annual mean discharge, in ft^3/s	2.20	1.02	1.04	.71
Annual runoff, in (ft^3/s)/ mi^2	2.79	3.18	3.25	2.23
Annual runoff, in inches	37.9	43.2	44.1	30.3
Precipitation, in inches	40.7	32.0	38.8	25.4
Ratio of annual runoff to annual precipitation	.93	1.35	1.14	1.19
Mudboil/depression area (derived values*)				
Total discharge, in ft^3/s*	248.	175.	221.	166.

† Water year refers to 12-month period from October 1 through September 30 of the following year.

†† Watershed area (0.70 mi^2) above Tully Farms Road diverted to Tributary 5 in June, 1992

* Calculated as value for watershed downstream of mudboil/depression area minus value for watershed upstream of mudboil/depression area

The range and distribution of sediment concentration at the MDA outflow after the diversion are plotted in figure 18. The total sediment load from the MDA before the diversion was 8,460 tons over 255 days or an average of 33.2 ton/d. After the diversion, and until the impoundment was completed in July 1993, the sediment load from the MDA was 6,010 tons over 415 days, or 14.5 ton/d. Although a 20-percent decrease in precipitation accounts for some of this decrease, peak loads were decreased three-fold between spring 1992 (February-April, 46.3 ton/d) and spring 1993 (February-April, 13.9 ton/d).

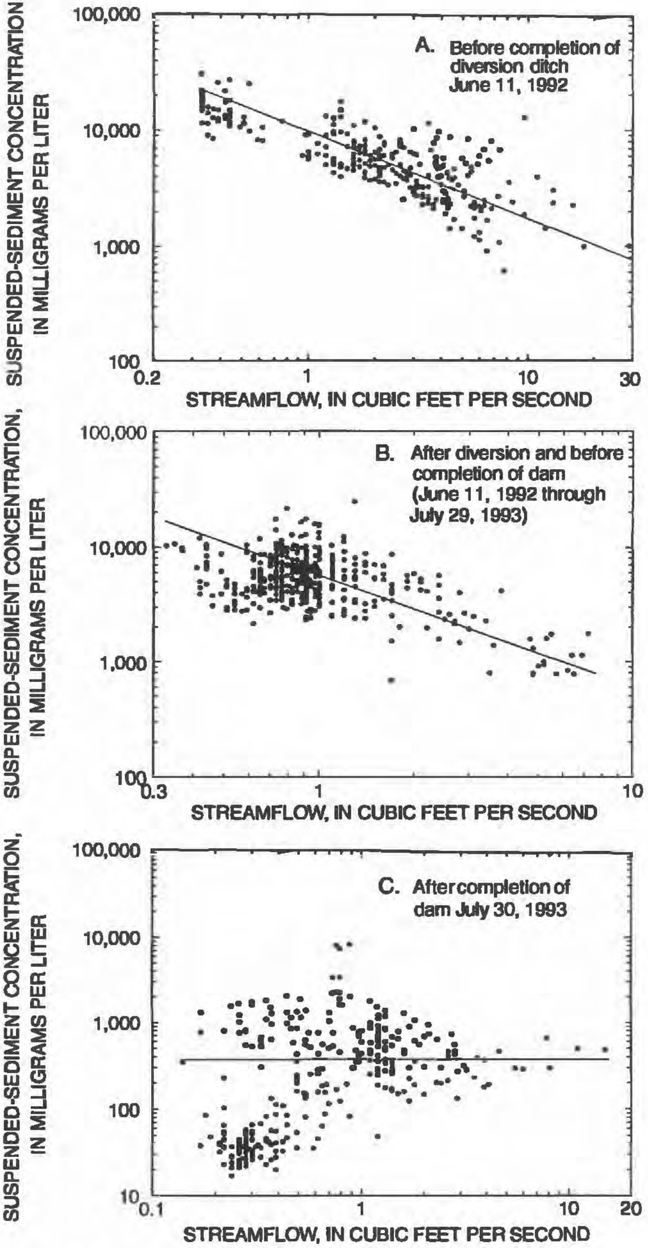


Figure 17. Relation between suspended-sediment concentration and streamflow at mudboil/depression area before and after remediation measures: A. Before completion of Tributary 6 diversion on June 11, 1992. B. After completion of diversion but before impoundment of water on July 29, 1993. C. After impoundment.

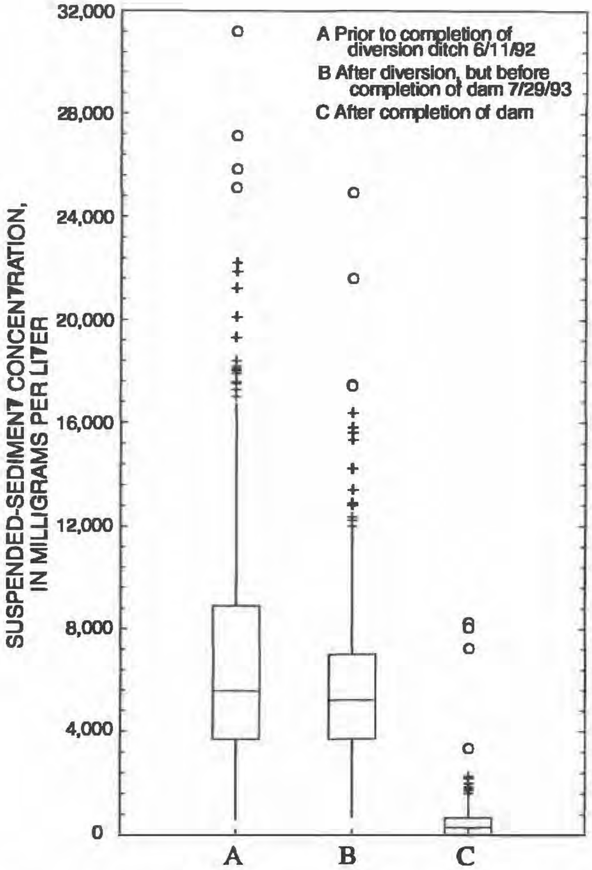


Figure 18. Distribution of suspended-sediment concentrations in water samples from the mudboil/depression-area outflow flume before and after remediation efforts.

Mudboil/Depression-Area Impoundment

A temporary dam was constructed in July 1993 at the outlet of the MDA to increase the lithostatic and hydrostatic pressure over the mudboil vents by trapping the fine sand and coarse silt in the pool behind the dam. As a result, MDA mudboils were covered by the impounded water and trapped sediment within the eastern area and the eastern parts of the northwestern and southwestern areas (fig. 14C). The northwestern area, being the newest and most active, was never fully inundated and continued to discharge a majority of the mudboil sediments in 1994.

Change in Sediment Concentration and Load

The MDA dam was closed on July 29, 1993, and impounded about 3.5 ft of water. Turbidity and sediment loads measured downstream of the dam immediately decreased when all of the fine sand and most of the silt fraction settled out before reaching the outlet. The decrease in the relation of sediment concentration to flow is apparent in fig. 17C, which shows that sediment concentration no longer correlated with flow after the impoundment was completed.

The sharp decrease in sediment concentrations and loads slowly reversed as the impounded area filled with sediment. The average sediment concentration during the 5 days preceding the closure of the impoundment dam on July 29, 1993, was 11,700 mg/L. Upon closure of the dam, sediment concentration decreased to 8,560 mg/L, then over the next 5 days decreased to 44 mg/L. The average sediment concentration for July 1-29 was 6,770 mg/L, and the average daily loading was 7.4 ton/d, whereas the average sediment concentration for August was 36 mg/L, and the average daily loading was 0.04 ton/d. Over the next 2 months, sediment concentrations increased nearly 10-fold (fig. 19C), and by November 1993, the impoundment was nearly full, and its effectiveness in trapping sediment was greatly diminished.

Sediment concentrations at the MDA outlet increased sharply in response to renewed mudboil activity during the first 2 weeks of November 1993. Several new mudboils were also observed within the MDA, and sediment discharged from these mudboils filled the impoundment. Average daily sediment concentrations at the MDA outlet from November 1993 through January 1994 were about 1,650 mg/L —well below the concentrations measured before the impoundment was created, and diminished during February 1994 (fig. 19C) as mudboil discharges decreased, but they increased gradually through mid-June, until the top of the outlet control structure was raised, increasing water levels 6 in. and causing another decrease in sediment concentration. Average daily sediment concentration from February 1 through June 20, 1994, was 508 mg/L. The effect of the 6-in. water-level rise was apparently short-lived, though, because fine-grained sediment quickly filled the additional volume, even though average daily sediment concentration from June 20 to September 30 was only 172 mg/L. A new mudboil developed in the southwest area (fig. 14C) at this time and discharged a large amount of sediment to the impoundment area; the increased sediment concentration in July and August 1994 (fig. 19C) could reflect this new mudboil. The sediment concentrations then slowly increased through the drought of 1995 as the impounded area became totally filled

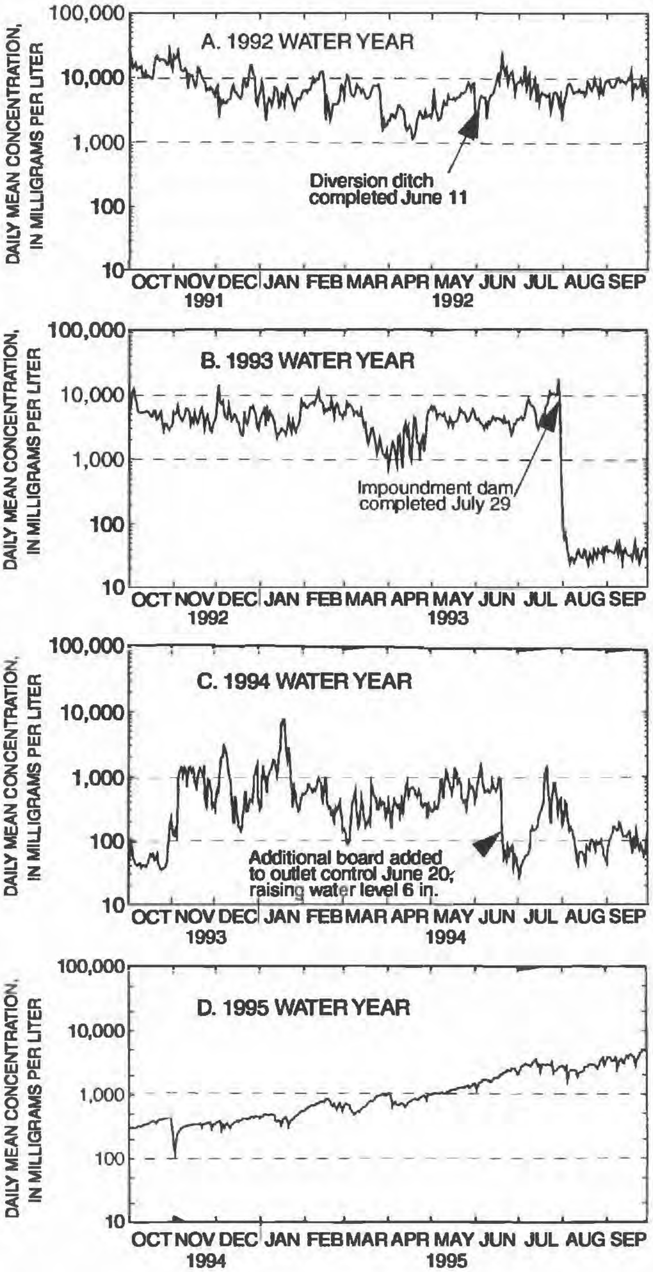


Figure 19. Daily mean suspended-sediment concentration at the mudboil/depression area outflow flume, water years 1992-95.

with sediment. By September 1995, sediment concentrations increased to over 3,000 mg/L, and the entire MDA became a mud flat with local areas of standing water.

Change in Hydraulic Head

Monitoring wells up- and downgradient of the impoundment dam were installed in June 1993 to determine whether the impounded water in the MDA would recharge the layered silty-clay and fine sand unit along Tributary 6, just east of the MDA. This layered unit and the remnant of at least one sand and gravel meander channel was found during the drilling of the monitoring wells. The massive red silty-clay unit was found below the layered unit, and screens for these wells were installed at the contact between these two units. Hydrographs for three wells in this area, and precipitation for the corresponding period (August 1993 – November 1995) are shown in figure 20.

Water levels in these wells fluctuate seasonally as a result of evapotranspiration during the growing season. The seasonal declines in water levels at all three wells (fig. 21) seem unaffected by the nearly steady water level in the impoundment. The degree of interaction between water in the impoundment and in the shallow, fine-sand layer unit is unknown, although the water level in well Od-440, upgradient of the MDA structure, remained much higher during the 1995 drought than that in the well downgradient of the dam (Od-439), which apparently went dry (fig. 20).

Depressurizing Wells

The third remediation approach entailed the installation of depressurizing wells near the collapsed Otisco Road bridge in December 1993 and January 1994 to reduce locally, the artesian pressure within the freshwater aquifer while holding the fine-grained sediments in place. Well screens (5-in. diameter) were placed in the coarse material at the bottom of the freshwater aquifer to avoid discharging the fine sand and silt from the upper part of the freshwater aquifer. The well on the west side of the bridge (Od-450) was screened in a medium to fine sand in December 1993, and flow rates after development ranged from 16 to 21 gal/min during the 1994-95 water years. The well on the east side of the bridge (Od-451) was screened in fine sand, and flow rates after development ranged from 3 to 5 gal/min.

In addition, three monitoring wells (Od-431, Od-403, and Od-434) were installed on the west side of the Otisco Road bridge before the depressurizing wells were drilled. These wells are about 35, 70, and 195 ft west, respectively, of the west-side depressurizing well (Od-450, fig. 3) and are completed in the top of the freshwater aquifer. A data logger connected to transducers in each well recorded

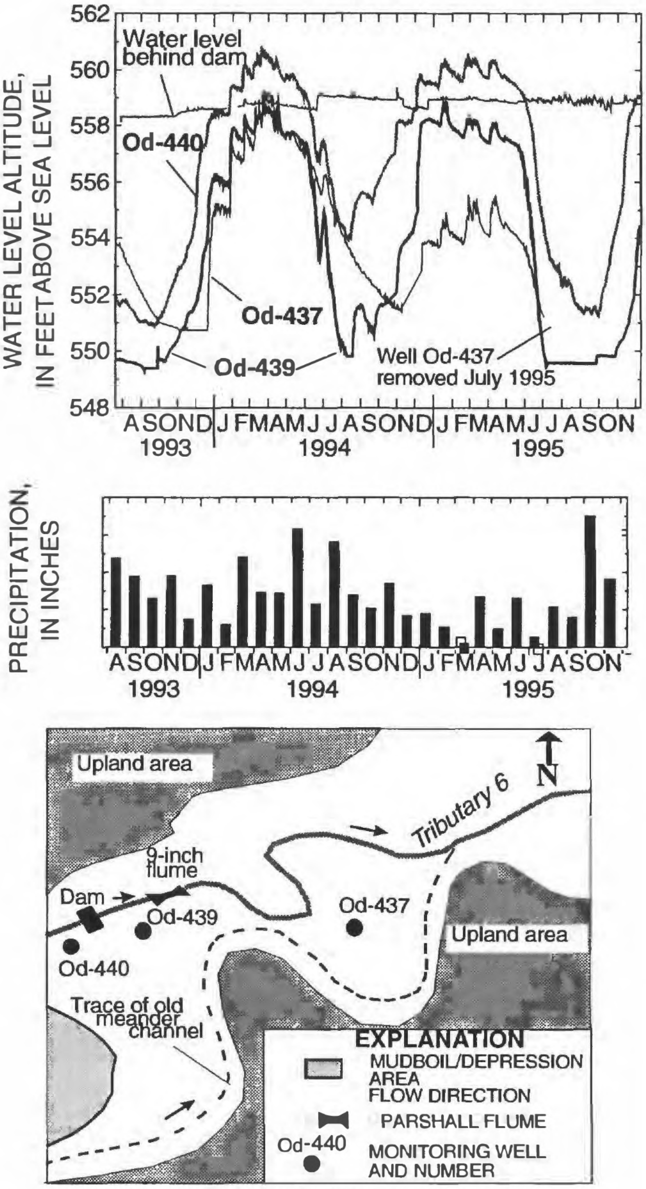
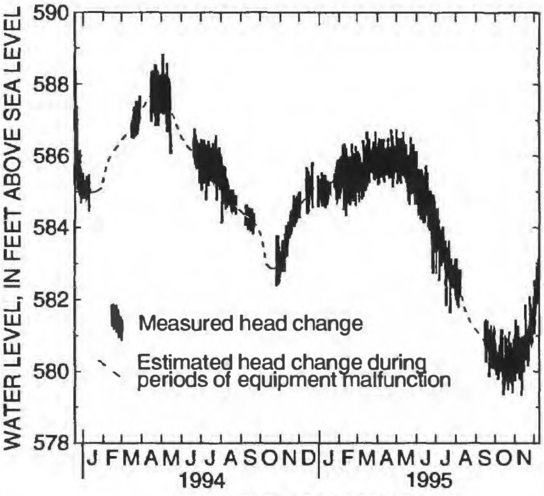


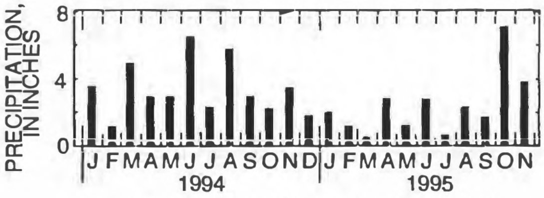
Figure 20. Water levels in monitoring wells downgradient of the mudboil/depression area outlet in relation to water levels controlled by outlet dam, and monthly precipitation recorded at Otisco Road rain gage. (General location is shown in fig. 3.)

artesian pressure in the freshwater aquifer; a separate transducer was used to record atmospheric pressure. Hydraulic head in the freshwater aquifer was recorded from December 1993 through December 1995 (fig. 21). Malfunctions and anomalous pressure readings prevented acquisition of a complete hydraulic-head record throughout 1994-95, and subsequent analysis indicated that well Od-403 had a leak in the casing and could not be used for artesian-pressure determinations. The remaining two wells provided hydraulic-head data for the upper part of the freshwater aquifer.

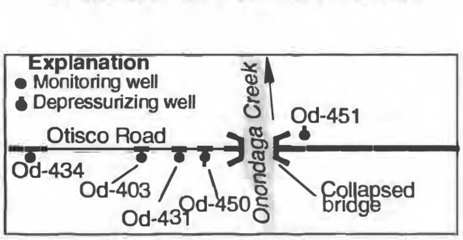
The west-side depressurizing well, developed during December 20-22, 1993, flowed freely on December 21 at a rate of 9 gal/min, and the two monitoring wells showed a head decline of 0.6 ft. When the final flow rate of 20 gal/min was obtained on December 22, the head fell an additional 1.6 ft. Total decline in artesian pressure at the two monitoring wells was 2.2 ft, or equivalent to about 1 lb/in.^{2} (fig. 22). The response to each change in flow rate took about 24 hours to reach equilibrium. The effect of the east-side depressurizing well (Od-451), which flowed at a rate of 3 gal/min, was minimal.



A. ARTESIAN HEAD



B. MONTHLY PRECIPITATION



LOCATION MAP

Figure 21. A. Artesian head at monitoring wells Od-431 and Od-435, 35 feet and 195 feet west of depressurizing well Od-450, December 1993 through November 1995; B. monthly precipitation recorded at Otisco Road rain gage.

Artesian pressures in the freshwater aquifer near the Otisco Road bridge from December 1993 to December 1995 ranged from a high of about 587.50 ft in April 1994 to a low of about 581.50 ft in November 1995 (fig. 22); the low pressure was during the 1995 drought. The annual range of fluctuation is about 5 ft, similar to many of the pressure-gage readings taken at other freshwater-aquifer wells along Onondaga Creek and around the MDA. Thus, the discharge of 20 to 25 gal/min from the two depressurizing wells had only a small effect; for example, a mudboil adjacent to the bridge foundation and well Od-450 continued to flow at an undiminished rate after both depressurizing wells were opened. (The mudboil that destroyed the Otisco Road bridge discharged at a rate of about 80 gal/min—nearly 3 times the combined flow of the two depressurizing wells.)

A short-term aquifer test was attempted at the west-side depressurizing well (Od-450) on December 22, 1994, to determine the effect of pumping from the freshwater aquifer. This well initially flowed at 18 gal/min before the test, and within 4 minutes into the test, the water level had declined 73 ft, or 70 ft below land surface, and remained fairly stable at a pumping rate of 55 gal/min. The effect at the nearby monitoring wells was not typical for a confined sandy aquifer; and no response was seen at the most distant monitoring well (195 ft away) until 30 minutes into the test. The water level in the nearby monitoring well fell initially, but then rose within the first 30 minutes; after 4 hours of pumping, the drawdown at the nearby well was about 15 ft, and the drawdown at the most distant well was only 2.5 ft.

The pump was turned off after 5 hours, and within 2 minutes, the depressurizing well was again flowing at about 18 gal/min; the two monitoring wells took an additional hour to begin recovery. The results of this test could be attributed to the differences in (1) the unit in which each well was completed, and (2) the permeability of the pumping and monitoring zones. The monitoring wells are finished in the upper part of the freshwater aquifer, where the materials are very fine sand and silt, whereas the pumping well is screened at the bottom of the freshwater aquifer in fine to medium sand. The intervening materials are locally variable and might contain layers of silt that divide the aquifer.

Although the results of this test could not be analyzed to determine aquifer properties, they did indicate that the lower part of the freshwater aquifer can be pumped to lower the artesian head locally. The test also indicated that, for a mudboil to discharge at rates of 80 gal/min (the rate measured at the Otisco Road bridge mudboil) and to discharge as much water and sediment as it did during 1991, the mudboil-vent diameter must exceed that of the depressurizing wells and be filled with coarse sand through its entire length.

Mudboil Hydrodynamics

Mudboils have been associated with land subsidence in the Tully Valley for nearly 100 years. Mudboil activity is limited to areas adjacent to Onondaga Creek upstream of Otisco Road and along Onondaga Creek Tributary 6, the lowest elevations in that part of the valley. The average head in the confined freshwater aquifer is about 20 ft above the valley floor, except along Onondaga Creek, where it is 30 to 40 ft above the streambed (fig. 11). Most areas of land subsidence are associated with a layered fine sand and silty-clay unit (unconsolidated deposit unit 5, in fig. 6) that underlies the valley floor between Rainbow Creek and Rattlesnake Gulf. Well-log data (figs. 6 and 7) indicate that the layered unit is thickest, and the massive silty-clay unit beneath it is thinnest, near the intersection of Otisco Road and Onondaga Creek. Initial mudboil activity probably occurred here, where artesian pressures along the creek are high, and the local geologic conditions provide a weakness (the layered fine-sand/silty-clay zone) in the massive silty-clay unit.

When the first mudboil erupted, it most likely discharged fresh, but turbid, water and fine sand that created a small volcanolike sediment cone. The continued discharge of sediment probably caused the land surface to slowly subside and, in time, to form a circular depression. As subsidence continued, new vents probably formed around the edge of the depression along a subsidence fracture as the original vent was closed or pinched off by the inward movement of subsidence blocks from the edge of the depression. (A subsidence fracture is the easiest pathway for artesian pressure to follow from the confined aquifer to land surface.) When new vents form, their discharge is extremely turbid from erosion of the fine-grained silty-clay confining layer by the movement of water and fine sand against the face of the subsidence fracture. The vent increases in diameter through erosion, but stabilizes as the vent tube fills with clean, coarse sand that conducts less turbid water from the confined aquifer to land surface. Sand in the lower part of the vent tube is coarse but grades from medium to fine near the top, and the finest particles continue to discharge at land surface. The continued discharge of sediment again allows the land surface to slowly subside and pinch off active vents, and the process of new vent formation, discharge, and subsidence continues.

Historically, growth of the mudboil area proceeded southward (upstream) along Onondaga Creek from the Otisco Road bridge area toward source areas of artesian pressure. As mudboil activity migrated away from the creek, the continued mudboil discharge and land subsidence created a mudboil field containing many inactive and diffusely discharging vents. Where sand-filled vents stabilize, land subsidence slows, and the mudboil field becomes an area of diffuse ground-water seepage in which only wetland (phreatic) plants survive, and the continued artesian pressure keeps the fine-grained sediments liquefied to nearly quicksandlike conditions.

Mudboils near or in a stream discharge sediment directly to the stream, and as discharge continues, land subsidence is accelerated, as demonstrated at the Otisco Road bridge, where a mudboil caused the bridge to collapse in less than 3 months. A slightly different situation has developed at the southern end of the Onondaga Creek mudboil corridor, where a large subsidence area has been growing for the at least 7 years. Deposition of alluvial coarse-grained sediments by Onondaga Creek in this subsidence area has slowed the rate of water and sediment discharge and of land subsidence, however.

Mudboil activity in the MDA is analogous to that in the mudboil corridor along Onondaga Creek. As mudboil activity increases in the MDA, the increased discharge of freshwater and sediment leads to increased land subsidence. The mudboil sediment is easily eroded and carried away by Tributary 6, and this removal leads to further mudboil discharge, land subsidence, and development of new mudboils; thus, the mudboil process, once begun, is self-perpetuating. Mudboil discharge and subsidence rates increased further as a hydraulic connection between the brackish-water aquifer and the upper freshwater aquifer developed, and the new source of water further increased the total discharge from the MDA and accelerated sediment loading to Onondaga Creek.

Cause of Mudboils

The time and location of the first mudboil eruption is unknown because no data are available, but the hydrologic and geologic information collected in this study allow an interpretation of mudboil persistence. Before this study, several researchers had developed theories to explain the cause of the mudboils, primarily those within the MDA (referred to in the 1970's and 1980's as the "King Farm" mudboils).

1. Getchell (1983) indicated that enhanced dissolution of evaporite deposits in the Salina Group, beneath the MDA, was related to the salt-solution mining operations further to the south and was the probable cause of subsidence at the King Farm. He indicated that dissolution of the evaporite beds caused collapse of the overlying bedrock and the subsequent collapse at land surface and postulated that: (1) the source of water discharging from the MDA was driven by artesian pressure, and (2) the water discharging from the MDA mudboils was a mixture of (a) water from deep sand and gravel deposits that underlie the thick glaciolacustrine deposits, and (b) water from bedrock that, at some time, was in contact with the evaporite deposits and was forced upward into the MDA as part of the deep regional flow system.
2. Rubin and others (1991) described the dissolution of the salt beds in terms of a naturally occurring "salt-front" moving southward in the evaporite deposits. The salt-solution mining operations further south altered the regional ground-water-flow pattern, and the combination of the two dissolution processes coincided beneath the MDA. When the two salt-dissolution processes met, the bedrock failed, eventually causing subsidence at the land surface, and the water discharged from the MDA was a mixture of water from the shale and evaporite deposits and water from the unconsolidated deposits.
3. Haley & Aldrich of New York (1991), in their report on mudboil occurrence, do not relate the mudboil phenomena at the MDA to any form of collapse in the bedrock or dissolution of evaporites below the MDA; rather, they state that the brackish water that discharges within the MDA comes from the western valley wall, along structurally induced planes of weakness that lie beneath Rattlesnake Gulf. They also state, on the basis of geochemical and isotopic data, that the mudboils in the Onondaga Creek corridor, specifically those at the Otisco Road bridge, are driven by water from the deep sand and gravel formation underlying the valley, and that mudboil activity appears to be greatest during periods of below-normal precipitation. Their statement is based on casual observation, however.

Water-quality data (tables 6 and 7) indicate that waters from two different aquifers drive mudboil activity in the MDA—the confined freshwater aquifer and the underlying confined brackish-water aquifer. The freshwater aquifer has low permeability because its upper two-thirds consist of fine-grained sediments, although the lower third contains medium sand to fine gravel in certain locations, such as near the MDA. Water in this area, except at mudboil vents, has the isotopic characteristics of older water (tritium levels are much below the decayed-tritium peak of the mid-1960's; see appendix 2) and a geochemical signature of both the shale and unconsolidated gravel deposits (Haley & Aldrich of New York, 1991). The brackish water does not necessarily flow from the bedrock at Rattlesnake Gulf to discharge points at the MDA along planes of weakness in the fine-grained deposits—it could flow through the coarse-grained sediments below the upper silty-clay unit that appear to extend under most of the valley. The general direction of flow in the brackish-water unit is northward, from the brine field to brackish-water springs at the base of Bare Mountain and, recently, to certain mudboils in the MDA. No data collected during this study indicate that periods of below-normal precipitation cause increased mudboil activity, but they do indicate that mudboil activity increases during the spring and fall recharge periods and after extended periods of heavy precipitation that provide ample ground-water recharge.

The data collected in this study have decreased the number of plausible theories to explain mudboils but do not indicate when and where the first mudboil eruption occurred. The following information illustrates the difficulty in identifying the time and location of mudboil origin but could help indicate where mudboils or land subsidence may occur in the future.

Onondaga Creek Mudboil Corridor

The initiation of mudboil activity in the Tully Valley has been attributed to both natural and human factors. The theories are numerous, but data to support most of them are lacking. The following theories can be supported by the data collected in this study.

Natural Causes

The stratigraphic column near the Otisco Road bridge area (fig. 7) indicates that the layered sequence of sediment here is less competent than the massive silty-clay unit elsewhere beneath the valley floor and can be most easily breached where the distance between the source-zone of artesian pressure and land surface is least—the area along Onondaga Creek (figs. 6, and 7). This layered sequence could slowly fail from the bottom upward through the process of hydraulic fracturing. (Hydraulic fracturing is defined by Sherard [1986, p. 907] as "the process whereby excessive pressure can concentrate along a zone of weakness and physically jack-open a crack and make it wider.") Although Sherard's work was primarily with horizontal hydraulic fracturing of impervious cores of dams, the physical process can operate vertically under the high artesian pressures found in the freshwater aquifer such that the artesian-pressured water and attendant sediment may have penetrated, in a wedgelike fashion, the overlying layered sand and silty-clay unit and forced the fine sediment upward through each of the thin confining layers. Hydraulic fracturing would occur during periods of above-normal precipitation and(or) high artesian pressure and, over time, would develop into a continuous "vent" of sand from the confined aquifer to land surface.

Conversely, the hydraulic connection between the confined aquifer and land surface may have developed from within the layered sediment sequence through its connection with the Rattlesnake Gulf alluvial fan. The Rattlesnake Gulf fan, near the western valley wall, has a higher hydraulic head than the layered sediment near Onondaga Creek and, through its hydraulic connection to the layered unit (fig. 6), may have overpressured the more permeable sand layers within this unit near Otisco Road and Onondaga Creek. Periodic rupturing of the upper sand and silty-clay layers could have resulted from excessive recharge, at the alluvial fan, that would have forced water to discharge upward through confining layers and ultimately to land surface near the creek. Over time, successively lower layers could have ruptured upward from the pressure differential, and a mudboil vent could have propagated downward to reach the confined, freshwater aquifer. Alternatively, a combination of these two processes—hydraulic fracturing from below and overpressured rupturing from above—could have caused the first mudboil vent. The initial eruption could have been relatively weak and might not have been noticeable during periods of high runoff because Onondaga Creek is naturally turbid during high-flow periods.

Another possible cause of mudboil development could be an earthquake—rapid shaking of the ground could cause the fine-grained sediments to liquefy and erupt through the structurally weaker layered unit. The only report of an earthquake before the 1899 newspaper article (see "Previous Studies of Mudboils" section) was from the mid-1840's; Clark (1849) reported "considerable agitation" south of the village of LaFayette and east of the Tully Valley. (See appendix 1). Liquefaction and mud-vent development, as described earlier, could have started the mudboil activity, and the high artesian pressures would then have continued the process.

Human-Induced Causes

Bailey-Loomis dam. The former Bailey-Loomis dam (location shown in fig. 7), just south of Otisco Road, was constructed in the early 1800's. The dam, estimated to have impounded at least 10 ft of water, may have overpressured the upper sand layers behind the dam. Downstream of the dam, this excessive hydraulic pressure could have created a zone of saturated soil or a discrete point of discharge such as a sandboil; similar sandboil development along river levees and downstream of dams in fine-grained alluvial sediments have been documented by the U. S. Army Corps of Engineers (1978). No reference to a dam failure or softening of the soil downstream of the dam could be found in the historical records, however. (The dam and mill were reportedly destroyed by a flood in the mid-1860's.) The earthquake of the mid-1840's, in conjunction with the impoundment of water behind the dam, could also have led to mudboil activity in the Tully Valley.

Brine field operations. Larkin (1950) noted that "excessive amounts of water" were initially injected into the brine wells to dissolve and lift the dense brine and discharge it at land surface. The Tully Lakes, which are 500 ft higher than the top of brine wells, were the source of the water used to lift the brine. Larkin (1950) also noted that 40 to 60 percent of this water was "lost" in this operation through leakage to fractures in the bedrock and(or) to the glacial deposits in the valley. This leakage could have increased hydraulic pressures in the weathered, fractured bedrock surface, in bedding-plane fractures, and, possibly, in the more permeable unconsolidated deposits in the valley; it also could have overpressured the confined aquifers and hydraulically fractured the layered sediment unit near the Otisco Road bridge and the clayey-till layer at the MDA. The time between initial solution brining operations (1890) and report of the Otisco Road mudboil (1899) was less than 10 years.

Mudboil/Depression Area (MDA)

The initiation of mudboil activity in the MDA also has been attributed to natural and human factors. Again, the data to support most theories are lacking, but the following theories can be supported by the data collected in this study.

Natural Causes

Local residents report that mudboil activity along Onondaga Creek Tributary 6, within what is now the MDA, began in the 1950's, whereas mudboil activity along the Onondaga Creek mudboil corridor began before 1900 and migrated southward from the Otisco Road area. Lateral expansion along the corridor north of Tributary 6 was limited by the elevation difference between the creek and the surrounding uplands, which are generally 10 to 15 feet higher than the creek bed. Where the mudboils approached Tributary 6, the sharp elevation change found elsewhere along the creek was absent, allowing lateral migration of mudboils up the tributary stream channel; three mudboil fields can be identified between Onondaga Creek and the MDA. Aerial photographs (U.S. Defense Mapping Agency) from 1936 and 1937 indicate the MDA to be a wetland area with several rounded scarps in what is now the eastern subsidence area (fig. 14A). The development of mudboils within this wetland area may have been part of the westward migration of mudboils up the tributary toward the artesian-pressure source area at Rattlesnake Gulf.

Human-Induced Causes

In 1931, a petroleum pipeline was installed along the valley floor and through the eastern part of the present MDA. Average pipeline burial depth was 3 ft below land surface and 5 ft below stream channels. Although no records of pipeline construction are available, the pipeline is assumed to have been buried with little difficulty within the layered sand and silty-clay unit, but it could have induced some flow from nearby subsidence fractures along Tributary 6, just downstream from the MDA. The log for well Od-406, adjacent to the pipeline (fig. 14A), and excavation for the downstream Parshall flume, both indicated that the layers within the layered sand and silty-clay unit are tilted downward, toward the east, indicating that active subsidence probably had already occurred in this area.

In June 1972, Hurricane Agnes brought large amounts of rain to the south-central part of New York State and caused extensive streambank and channel erosion along the entire pipeline route. In the Tully Valley, the pipeline was exposed in three tributary channels draining to Onondaga Creek, the northernmost of which was within the MDA. By 1974, the pipeline company had reburied the pipeline at each stream crossing. At the MDA, this reconstruction might have lowered the pipeline into the underlying massive silty-clay unit, and, if subsidence fractures were present in this deeper trench, they would form a new pathway for mudboil development.

Brackish-water Discharges

The change of mudboil discharge from fresh to a mixture of fresh and brackish has occurred slowly in the MDA since the late 1970's. Even though data to document this change are available, the reason(s) for change, discussed below, are in dispute.

Natural Flow

Mudboil development and land subsidence within the MDA became increasingly active in the late 1970's and early 1980's. As the east and southwest subsidence areas developed, the mudboils discharged increasing amounts of water and sediment, leading to new mudboils and increased expansion of the two subsidence areas. The sediment-size distribution, as determined by split-spoon sampling in the freshwater aquifer near the MDA, indicates more coarse material than was observed near the Otisco Road bridge area, especially near the bottom of the aquifer, where fine gravel was found during the drilling of well Od-412. These coarse materials, which have a high permeability, allow increased mudboil discharge and subsidence rates and thereby decrease the hydraulic head in the area of increased discharge.

The decreased hydraulic pressure in this part of the freshwater aquifer, coupled with the higher hydraulic pressure in the underlying (brackish-water) aquifer, may have been sufficient to cause hydraulic fracturing of the confining clayey-till unit between the aquifers. The brackish water could then enter the upper aquifer, mix with the freshwater, and flow upward through existing mudboil vents. Continued discharge and erosion of the confining unit would produce a direct connection between the two aquifers and also would create more vents, thereby increasing the rate of water and sediment discharge and land subsidence. The northwestern subsidence area, in which nearly all mudboil vents discharge brackish water, could be the direct result of increased discharge of brackish water from the lower aquifer.

Human-Induced Flow

The salt-solution-mining operations in the Tully Valley ceased production in the late 1980's. Before closure of the operations, about 1Bgal of brine per year was flowing to Syracuse for production of potash. Cessation of pumping from the brine field allowed the unconsolidated and bedrock aquifers to establish a new hydraulic equilibrium that differs from that of the pre-mining period, in that (1) discrete water-bearing fractures in the bedrock are now hydraulically connected through channels created by the collapse, and (2) fracturing of bedrock over the solution-mined areas, and the hydraulic connection between the bedrock water-bearing zones and the unconsolidated deposits, is increased. Flow can now occur (1) through the weathered bedrock surface, (2) wherever the water-bearing fractures are exposed along the valley walls north of the brine fields, and (3) wherever the weathered-bedrock and water-bearing fractures are in direct contact with the alluvial-fan deposits. The new equilibrium has resulted in a lowered water table along the valley walls, especially near the brine fields, and an increased hydraulic head beneath the valley floor. Water quality has also changed as a result of the increased connection between brackish water from the salt formations and the fresher water in the upper aquifers. Brackish water entering the unconsolidated deposits can increase the concentration of many chemical constituents in the freshwater now flowing through the unconsolidated aquifers, and the higher head beneath the valley provides for increased mudboil activity and subsequent land subsidence.

Tully Valley Flow Dynamics

Mudboil activity is now confined to areas along Onondaga Creek south of Otisco Road, and along Tributary 6. Historic information is inadequate to indicate which of the above-cited theories is the most accurate, and the data from this study do not relate any particular mudboil area to any specific hydrogeologic change in the Tully Valley. Geochemical and isotopic data can be used to describe the present flow conditions and to identify the sources and age of water, and to delineate probable flow paths within the valley, but to relate hydrologic changes in the valley to changes in mudboil activity would require a long-term base of information.

An attempt to define long-term changes in the Tully Valley flow system entailed the use of dendrochronology (tree-ring analysis). After the April 1993 landslide, interviews with residents living south of the slide indicated that the flow of a freshwater stream emanating from a wetland near the foot of Bare Mountain (Nickols Road wetland, fig. 2), south of the landslide area, had increased, and a hydrogen sulfide smell and salty taste to the water had become noticeable within the last 5 to 10 years, especially during the summer. The source of this stream is a series of fresh and sulfurous springs at the foot of the hillside; the freshwater springs are fed by runoff from the hillside, whereas the sulfurous springs are fed from the shallow weathered and fractured bedrock. These springs are chemically similar to those within the backscarp area of the 1993 landslide (LS-4) and the backscarp area of older slides (LS-2 and LS-1) further north on Bare Mountain (fig. 2).

The springs south of the most recent landslide, at the foot of Bare Mountain, discharge to a cattail wetland area that contains a few white pines and hemlocks. This type of wetland does not usually support white pine, a species that is not water-tolerant; too much water would drown the roots and retard tree growth and possibly kill the tree. The presence of white pines in this environment, if they are old enough, might indicate long-term changes in the amount of water flowing into this wetland.

The growth rates of the white pines were determined by tree-ring analysis. A series of increment borings were collected from 28 trees within, adjacent, and uphill of the Nickols Road wetland, south and west of Nickols Road (fig. 2). Two borings per tree were collected and sent to the USGS tree-ring laboratory in Reston, Va. Results indicate that tree growth dates back to the 1870's in the oldest trees and that the growth rate was good until around 1890, when it began a decline that lasted until around 1960, when a new growth period began. The improved growth continued until the mid- to late-1980's, when another decline occurred (Thomas Yanosky, U.S. Geological Survey, written commun., 1995). These growth-rate changes are not seen in all trees because they are of differing ages and represent differing locations within the wetland. The changes in growth rate cannot be related to any trends in air temperature, precipitation, or other factors related to climate. Yanosky further states:

> The initial suppressed growth, followed by the dramatic increase in about 1960, and the recent growth decline, apparently are all caused by a single variable other than climate.

An assessment of the general hydrology of the valley since the late 1800's indicates that the largest change to affect the ground-water system was the brine-production process, whereby freshwater was injected into the salt beds to dissolve the salt, and a saturated brine was removed. In the early 1890's "excessive amounts of water" (Larkin, 1950) were needed to get the brine wells to flow, and about 50 percent of this water was lost to the bedrock or to unconsolidated deposits in the valley. As well-pumping technology improved after the turn of this century, the amount of injected water decreased, but enough water was still used to keep the brine levels near the top of the well casings. Finally, in the 1940's, submersible pumps were used that required injection of just enough water to dissolve the salt and produce a saturated brine. In the late 1950's, the eastern brine-field area was closed, and Tully Lakes water was no longer injected into the western brine-field wells because the brine-field operator found that the ground-water system could supply sufficient water for salt dissolution. The ensuing ground-water withdrawals lowered water levels in the unconsolidated deposits in the Tully Valley by as much as 70 ft during the summer of each year (fig. 15) until 1986, when brine withdrawals were reduced by 90 percent as the potash production was closed down. All brine withdrawals ceased in early 1988.

Although the major changes in solution brine-mining operations can be related to the changes in growth rates of white pines in the Nickols Road wetland, 2.5 mi north of the northern end of the solution mining fields, they cannot be linked to discrete events in the mudboil areas of the Tully Valley. Nevertheless, the brining operation altered the general movement of water within the bedrock of the valley and could also have changed the hydraulic conditions in the unconsolidated deposits. The ground-water flow system was increasingly affected as solutioning of all four salt layers increased. The effect of the ground-water withdrawals can be seen in water-level changes during 1983-95 at well Od-460 (fig. 15) and caused a 150-ft deep artesian well drilled on Webster Road in 1953 to cease flowing in 1959, when water levels dropped 25 ft below land surface (Gray, 1979). The effects appear to extend beyond the mudboil areas and northward to at least the wetland area near Nickols Road and, probably, to the well on Webster Road.

Remediation Efforts and Projections

The remediation efforts in the mudboil area (diversion of Tributary 6 and the MDA impoundment) substantially reduced sediment loading to Onondaga Creek but did not restore Onondaga Creek to pre-1950 conditions, nor have they substantially reduced the rate of land subsidence in the MDA. The depressurizing wells near the Otisco Road bridge over Onondaga Creek lowered the artesian pressure but did not slow the discharge from nearby mudboils. The following sections outline the results of remediation efforts in these areas and suggest additional procedures to alleviate mudboil activity.

Mudboil/Depression Area (MDA)

Diversion of water from the upper part of Tributary 6 to Tributary 5 has reduced the amount of sediment transported from the MDA to Onondaga Creek; it also has reduced the amount of recharge available to the alluvial fan between Tully Farms Road and the MDA. These reductions in flow to the MDA have reduced the sediment loading from the MDA to Onondaga Creek by almost 30 percent.

Although the impoundment at the outlet of the MDA initially reduced sediment loadings to Onondaga Creek, it became filled with sediment after 4 months and now can retain only the coarse fraction of the mudboil discharge. The impoundment decreased sediment loading to Onondaga Creek by more than 80 percent during 1994, but it also has increased the hydrostatic and lithostatic load on the MDA and thereby could cause an increase in the discharge of ground water to the Onondaga Creek mudboil corridor. Although the increase in flow is not a problem at present, it could give rise to new mudboil activity that would be difficult to control in the future.

Artesian pressure in the MDA area could be reduced if several depressurizing wells, finished in the coarse sediments in the lower part of the fresh water aquifer, could be installed around the MDA; the reduction in water and sediment discharge from MDA mudboils would, in turn, lead to decreased land subsidence. Allowing depressurizing wells to freely discharge could also cause an increase in the flow of brackish water, however, and would increase the salinity of total mudboil discharge to Onondaga Creek. The depressurizing wells would need to be carefully regulated to maintain a relatively fresh discharge without inducing flow from the deeper, brackish-water aquifer.

The capture of mudboil sediments in the MDA could be increased if the impoundment outlet were reconstructed at a higher elevation; the increased lithostatic and hydrostatic pressure might also make the depressurizing wells more efficient. The increased load on the MDA mudboils might cause mudboil activity to move downgradient to the Onondaga Creek mudboil corridor, where the artesian pressure might be more easily relieved in the formerly quiescent mudboil areas. The higher impoundment structure would be constructed only after operation of the MDA depressurizing wells begins. The use of depressurizing wells should slow the overall discharge of mudboils in the MDA and reduce sediment discharge and land subsidence in the MDA, thereby reducing the rate at which the impounded area would fill with sediment.

Onondaga Creek Mudboil Corridor

Even though the depressurizing wells near the Otisco Road bridge lowered the artesian head in this area by several feet, their installation did not slow or stop the flow from nearby mudboil vents. An aquifer test at the west-side depressurizing well indicated that substantial drawdowns (in the range of 70 ft) could be attained in the freshwater aquifer, but the expense of operating and maintaining these wells would be prohibitive. Additional depressurizing wells along the Onondaga Creek mudboil corridor from its southern end to north of the Otisco Road bridge area would need to be installed and discharging before any additional water would be impounded at the MDA to control potential migration of mudboil activity to the corridor.

Proposed Efforts at Alluvial Fans

The alluvial fan at the mouth of Rattlesnake Gulf and, to a lesser extent, that at Rainbow Creek, have been identified as source areas of artesian pressure that drives mudboil activity; thus, consideration of either (1) controlling the amount of water that enters the alluvial fans from the two streams, or (2) pumping the water from the alluvial fans, could be considered. Lining the creek bottoms from the bedrock/gravel contacts to Onondaga Creek would sharply reduce infiltration but would be expensive to build and maintain. The installation of pumping wells in one or both fans and piping the water directly to Onondaga Creek could reduce the hydraulic head in the freshwater aquifer and thereby reduce the amount of water discharging from the mudboils.

The Rattlesnake Gulf alluvial fan probably contributes a greater amount of water than the Tully Moraine to the freshwater aquifer in this section of the valley. Water removed by one or more pumping wells finished in the Rattlesnake fan could be used as part of a public water-supply system for homes whose drinking-water source was lost after the Tully Valley landslide of 1993. Evaluation of the potential yield from the Rattlesnake Gulf alluvial fan, the quality of water, and cost of developing a public water-supply and conveyance system were beyond the scope of this study, however. ☐

SUMMARY

Mudboil activity and land subsidence in the Tully Valley were first documented nearly 100 years ago and recurred intermittently until at least the 1950's. Since then, mudboil activity has become more persistent, and the rate of discharge from the mudboils has increased; this, in turn, has increased sediment loading to Onondaga Creek and resulted in land subsidence in both the Onondaga Creek mudboil corridor and the mudboil/depression area (MDA). The water discharged from both areas has historically been fresh until the late 1970's, when specific conductance and chloride concentrations in the MDA discharge increased, indicating a possible hydraulic connection to the underlying brackish-water aquifer.

The first documentation of mudboils in the Tully Valley (1899) may not represent their earliest appearance, and whether they were caused by natural factors or resulted from salt solution-mining operations, is unknown. Once started, however, mudboil activity has been self-perpetuating. By the late 1970's, water discharging from MDA mudboils was from the shallow, freshwater aquifer and the underlying brackish-water aquifer.

In the fall of 1991, the USGS began the first systematic assessment of quantity and quality of the water entering and leaving the MDA. Mudboil discharge is driven by artesian pressure in fine- to coarse-grained sediments of the freshwater aquifer, which is confined by a 60-ft layer of silt and clay. Artesian pressures in this aquifer are about 20 ft above land surface over most of the Tully Valley floor but more than 30 ft above land surface along Otisco Road near Onondaga Creek. Recharge is from the Tully (Valley Heads) Moraine to the south and from the alluvial fans at Rattlesnake Gulf and Rainbow Creeks. The Rattlesnake Gulf fan is the larger and is the most likely source of the additional artesian pressure in the freshwater aquifer in the area of Otisco Road near Onondaga Creek, the location of the first reported mudboil in 1899.

Data collected in this study indicate that suspended-sediment concentrations at the MDA outflow decreased from 31,210 mg/L in March 1992 to 17 mg/L after installation of a temporary dam and impoundment at the outlet of the MDA. Diversion of water from the upper part of Onondaga Creek Tributary 6 to prevent it from entering the MDA had little effect on sediment concentrations at the MDA outflow—the median concentration before diversion was 5,570 mg/L and after the diversion was 5,215 mg/L. The installation of the impoundment at the MDA outlet on July 29, 1993 reduced median sediment concentrations at the outflow to about 290 mg/L. During 1995, after the impounded area had become filled with sediment, the median sediment concentration at the outflow rose to about 1,300 mg/L.

Suspended-sediment loads from the MDA totaled 15,600 tons for water years 1992-95. Total measured sediment load from the MDA before diversion of the upper watershed of Tributary 6 (October 1, 1991 to June 12, 1992) was 8,462 tons or an average of 33.2 ton/d; total sediment load after the diversion, but before operation of the impoundment (July 29, 1993), was 6,014 tons or 14.5 ton/d. A 20-percent decrease in precipitation during that period was also partly responsible for the reduced sediment load. The sediment load during the 14 months from completion of the impoundment through September 1994 decreased to 508 tons, an average of about 1.4 ton/d. In the 1995 water year, the monthly sediment load slowly increased from about 14 tons during October 1994 to more than 100 tons in September 1995, for a total of 657 tons for the year, or an average of 1.8 ton/d.

Particle-size analysis before completion of the impoundment indicated that, by the time sediment reached the MDA outflow, it consisted of 30 to 60 percent clay and 80 to 100 percent silt-sized or smaller sediment and never contained more than about 20 percent sand. After completion of the impoundment, 50 to 80 percent of the sediment was clay, and nearly all was silt-sized or smaller.

The diversion of water from Tributary 6 in June 1992 decreased the amount of dilution in the MDA from the upstream watershed and caused specific conductance and concentrations of some constituents in the MDA outflow, such as dissolved calcium, magnesium, sodium, chloride, sulfate, and dissolved solids to be significantly higher in water years 1993-95 than in 1992. Analysis of water samples from upstream and downstream of the MDA, and of samples from mudboils within the MDA, indicate that the freshwater aquifer is the source of water for some mudboils, and the brackish-water aquifer is the source of others. Specific conductance of water from the freshwater aquifer ranged from about 400 µS/cm to nearly 900 µS/cm, and dissolved chloride and dissolved solids concentrations ranged from 37 to

430 mg/L and 215 to 463 mg/L, respectively. Specific conductance in the brackish-water aquifer, as determined from samples collected at (a) two mudboils in the northwestern part of the MDA, (b) observation wells (Od-412, 420 ft depth;, Od-416, 298 ft depth; and , Od-419, 42 ft depth), and (c) springs in landslide areas at the foot of Bare Mountain, ranged from about 17,000 to 28,000 µS/cm; chloride concentrations ranged from about 2,000 to 7,100 mg/L; and dissolved solids concentrations ranged from 4,200 to 12,800 mg/L.

The largest landslide in New York State in the last 75 years occurred on April 27, 1993, at the foot of Bare Mountain. This was the fourth in a series of slides that have occurred there, but no report of the first three slides is available. Slope instability in the area of the slide was reported as early as May 1990. After the slide, intermittent mudboil activity at several springs within the backscarp of the slide was reported. Water from these springs ranges from freshwater discharge at the colluvial slope of Bare Mountain, to brackish water (as saline as sea water) discharge from the bedrock.

The Onondaga Lake Management Conference began remediation efforts in 1992 to decrease mudboil discharge. Diversion of water from the upper part of Tributary 6 to Tributary 5, followed by impoundment of water and sediment at the MDA outflow, decreased mudboil-sediment discharge to Onondaga Creek by about 80 percent. Depressurizing wells installed near the collapsed Otisco Road bridge seem to have reduced sediment discharge and may have stabilized the area around the bridge; alternately, mudboil activity may have migrated away from this area. Although some remediation efforts have been successful, further work is needed at the MDA and along Onondaga Creek to lower artesian heads and reduce the discharge of fine-grained sediments. Left unchecked, mudboil activity will persist along the creek, but most of the mudboil activity and land subsidence will be within in the MDA as subsidence moves toward the Rattlesnake alluvial fan—one of the sources of artesian pressure in this area. Mudboil activity is greatest during the spring and late fall, when artesian pressures increase rapidly from seasonal recharge to the confined freshwater and brackish-water aquifers. The gradual increase in brackish-water discharge at the MDA may continue as the hydraulic connection between the lower to the upper aquifer develops over time. Remedial activities may reduce mudboil activity and land subsidence, but mudboils will persist in the Tully Valley as long as the two confined aquifers have hydraulic heads well above land surface.

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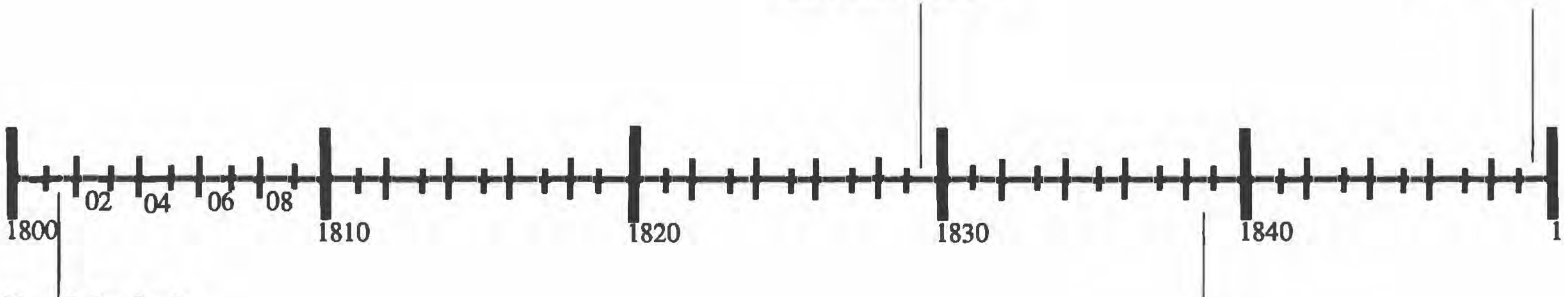
HISTORICAL TIMELINE—TULLY VALLEY MUDBOILS

Compiled by Valerie E. Holliday and Meghan L. Hodgins
Volunteers for Science - U. S. Geological Survey

Note : Large, boldface numbers refer to sources listed on pages 64-65 of Appendix I.

1829 — Map identifies Otisco Rd. and Tully Farm Rd. (formerly Christian Hollow Rd.) as incomplete, with industrial buildings in Rattlesnake Gulf, and village of Christian Hollow (Cardiff) 2.5 mi north of future mudboil area. **2**

1849 — Report of "considerable agitation" by an earthquake several years earlier, "chasms" at a farm south of LaFayette village. **4**



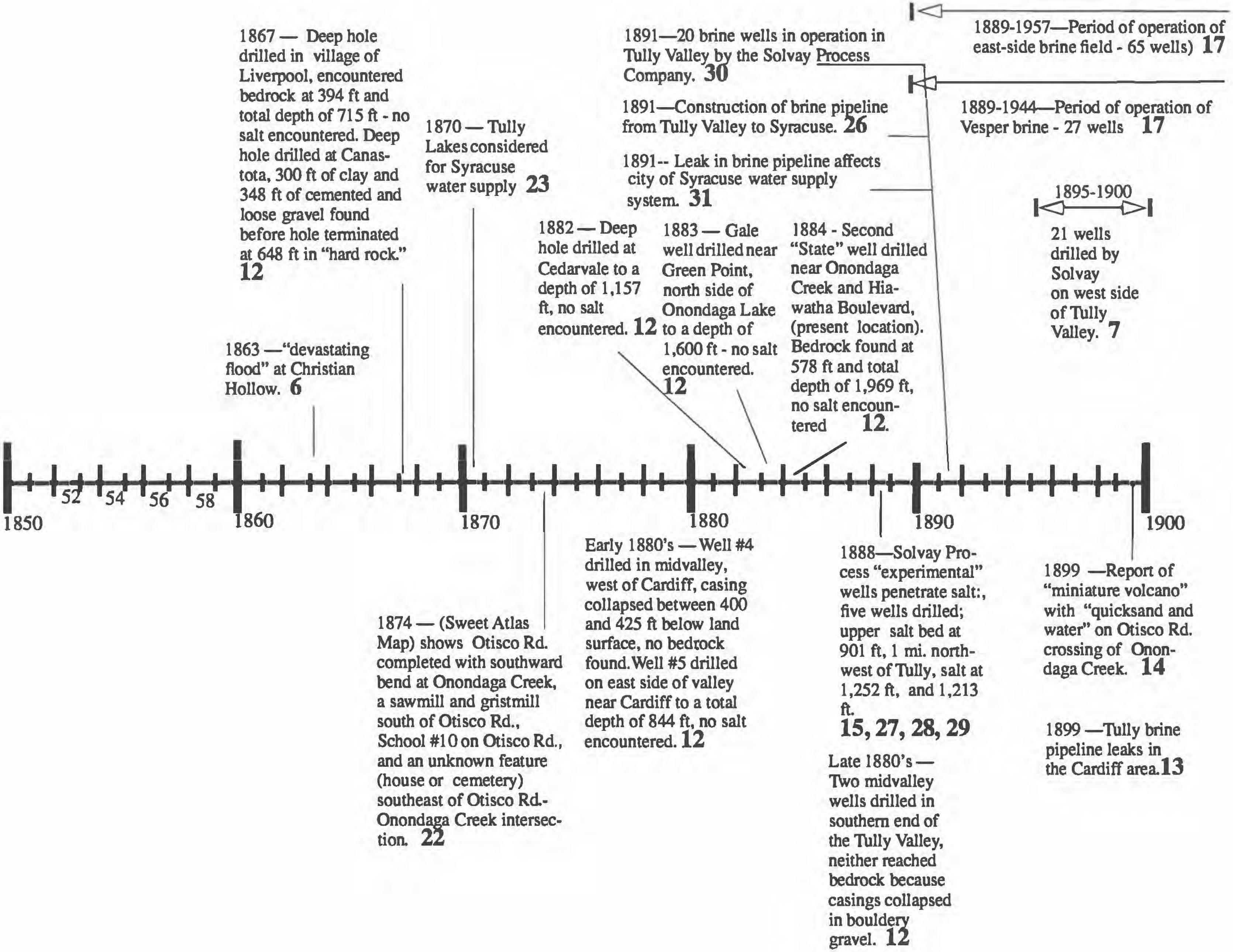
1801 — Bailey family moved to Tully Valley. Built and operated mill shortly thereafter.

Ownership transferred to Loomis (by marriage) around 1825.

Major flood partially destroyed mill in 1863; mill in decline in 1880's.

Property bought by brine-mining company in 1902. **6**

1838 — First "State" well drilled in the Syracuse area in search of salt beds. Hole drilled to a total depth of 600 ft into the Niagara Limestone. (Lockport Dolomite?) **12**



1863 —"devastating flood" at Christian Hollow. 6

1867 — Deep hole drilled in village of Liverpool, encountered bedrock at 394 ft and total depth of 715 ft - no salt encountered. Deep hole drilled at Canastota, 300 ft of clay and 348 ft of cemented and loose gravel found before hole terminated at 648 ft in "hard rock." 12

1870 — Tully Lakes considered for Syracuse water supply 23

1874 — (Sweet Atlas Map) shows Otisco Rd. completed with southward bend at Onondaga Creek, a sawmill and gristmill south of Otisco Rd., School #10 on Otisco Rd., and an unknown feature (house or cemetery) southeast of Otisco Rd.-Onondaga Creek intersection. 22

Early 1880's — Well #4 drilled in midvalley, west of Cardiff, casing collapsed between 400 and 425 ft below land surface, no bedrock found. Well #5 drilled on east side of valley near Cardiff to a total depth of 844 ft, no salt encountered. 12

1882 — Deep hole drilled at Cedarvale to a depth of 1,157 ft, no salt encountered. 12

1883 — Gale well drilled near Green Point, north side of Onondaga Lake to a depth of 1,600 ft - no salt encountered. 12

1884 - Second "State" well drilled near Onondaga Creek and Hiawatha Boulevard, (present location). Bedrock found at 578 ft and total depth of 1,969 ft, no salt encountered 12.

1888—Solvay Process "experimental" wells penetrate salt:, five wells drilled; upper salt bed at 901 ft, 1 mi. northwest of Tully, salt at 1,252 ft, and 1,213 ft. 15, 27, 28, 29

Late 1880's — Two midvalley wells drilled in southern end of the Tully Valley, neither reached bedrock because casings collapsed in bouldery gravel. 12

1889-1957—Period of operation of east-side brine field - 65 wells) 17

1889-1944—Period of operation of Vesper brine - 27 wells 17

1891—20 brine wells in operation in Tully Valley by the Solvay Process Company. 30

1891—Construction of brine pipeline from Tully Valley to Syracuse. 26

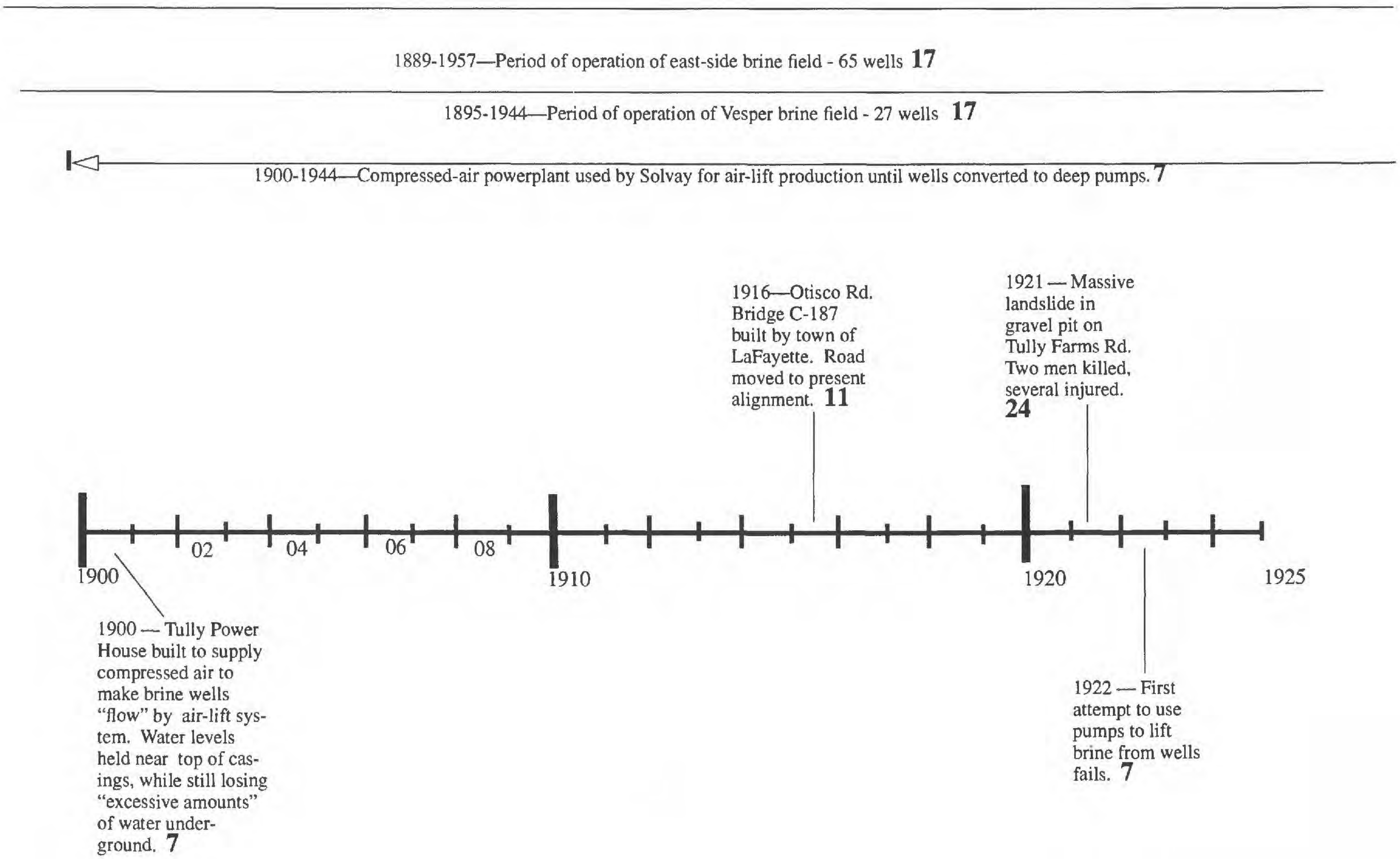
1891-- Leak in brine pipeline affects city of Syracuse water supply system. 31

1895-1900

21 wells drilled by Solvay on west side of Tully Valley. 7

1899 —Report of "miniature volcano" with "quicksand and water" on Otisco Rd. crossing of Onondaga Creek. 14

1899 —Tully brine pipeline leaks in the Cardiff area. 13



1889-1957—Period of operation of east-side brine field - 65 wells **17**

1895-1944—Period of operation of Vesper brine field - 27 wells **17**

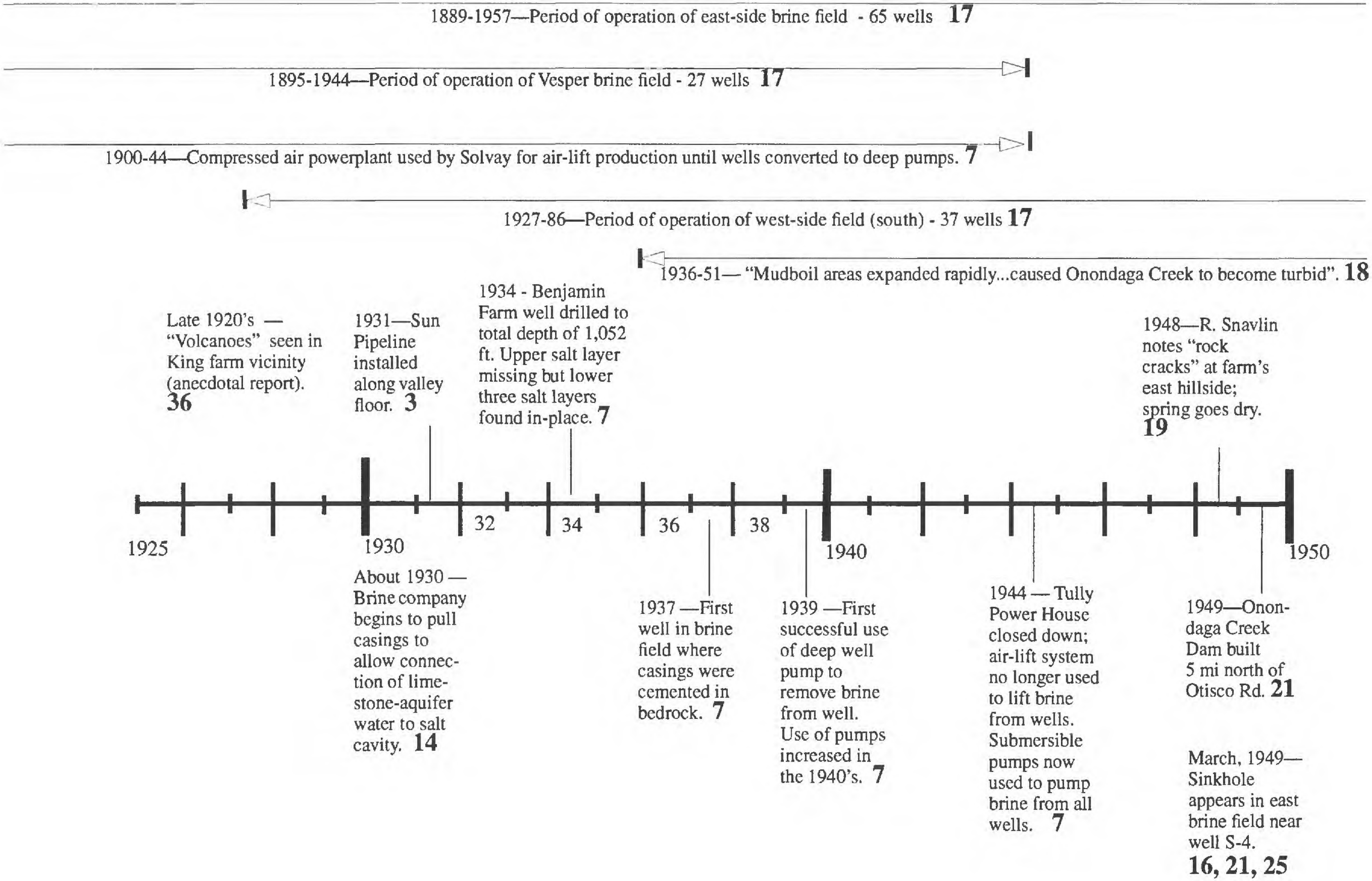
1900-1944—Compressed-air powerplant used by Solvay for air-lift production until wells converted to deep pumps. **7**

1900 — Tully Power House built to supply compressed air to make brine wells "flow" by air-lift system. Water levels held near top of casings, while still losing "excessive amounts" of water underground. **7**

1916—Otisco Rd. Bridge C-187 built by town of LaFayette. Road moved to present alignment. **11**

1921 — Massive landslide in gravel pit on Tully Farms Rd. Two men killed, several injured. **24**

1922 — First attempt to use pumps to lift brine from wells fails. **7**



1889-1957—Period of operation of east-side brine field - 65 wells **17**

1895-1944—Period of operation of Vesper brine field - 27 wells **17**

1900-44—Compressed air powerplant used by Solvay for air-lift production until wells converted to deep pumps. **7**

1927-86—Period of operation of west-side field (south) - 37 wells **17**

1936-51— "Mudboil areas expanded rapidly...caused Onondaga Creek to become turbid". **18**

Late 1920's — "Volcanoes" seen in King farm vicinity (anecdotal report). **36**

1931—Sun Pipeline installed along valley floor. **3**

1934 - Benjamin Farm well drilled to total depth of 1,052 ft. Upper salt layer missing but lower three salt layers found in-place. **7**

1948—R. Snavlin notes "rock cracks" at farm's east hillside; spring goes dry. **19**

About 1930 — Brine company begins to pull casings to allow connection of limestone-aquifer water to salt cavity. **14**

1937 —First well in brine field where casings were cemented in bedrock. **7**

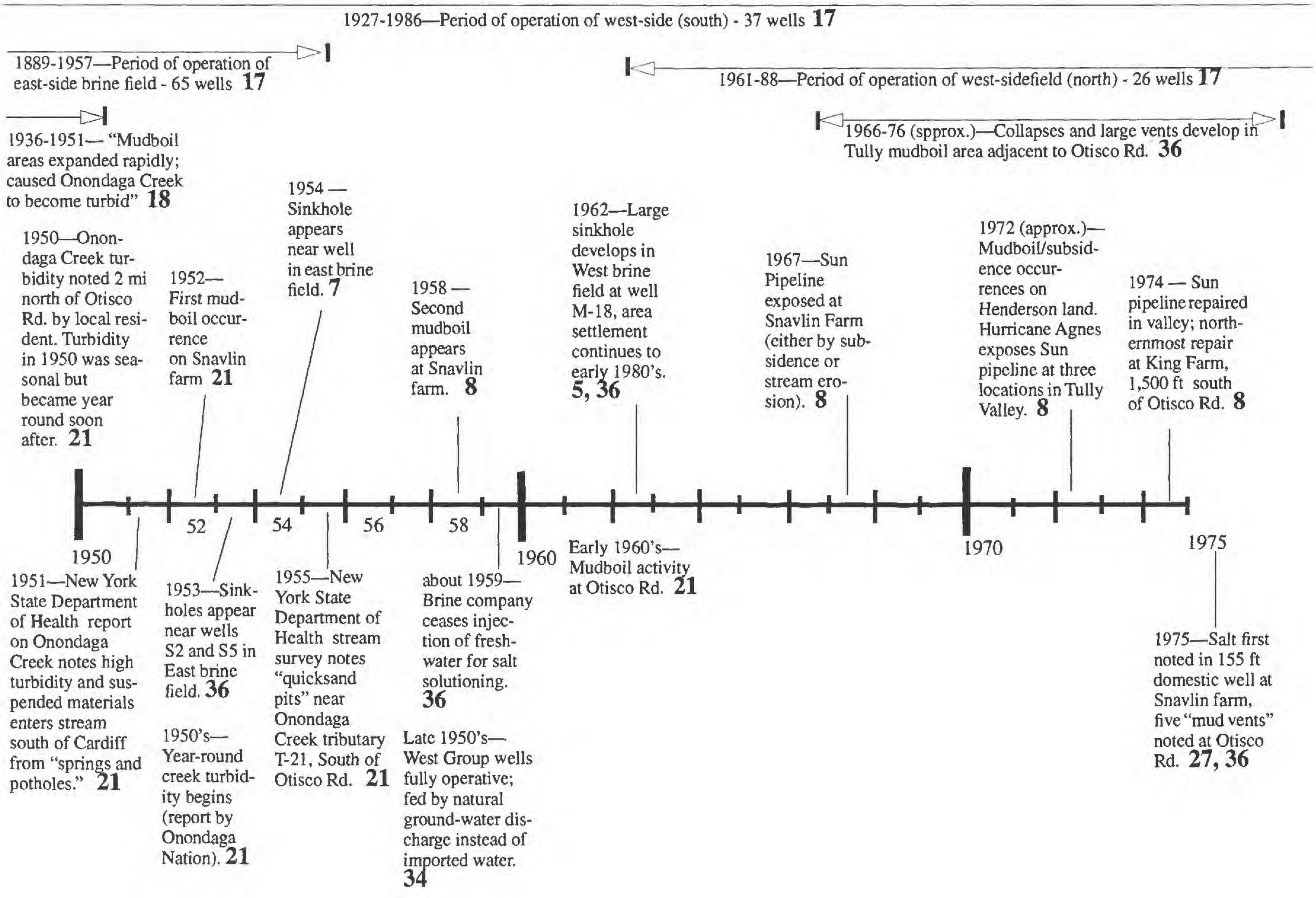
1939 —First successful use of deep well pump to remove brine from well. Use of pumps increased in the 1940's. **7**

1944 — Tully Power House closed down; air-lift system no longer used to lift brine from wells. Submersible pumps now used to pump brine from all wells. **7**

1949—Onondaga Creek Dam built 5 mi north of Otisco Rd. **21**

March, 1949—Sinkhole appears in east brine field near well S-4. **16, 21, 25**

APPENDIX I



1927-1986—Period of operation of west-side (south) - 37 wells **17**

1889-1957—Period of operation of east-side brine field - 65 wells **17**

1961-88—Period of operation of west-sidefield (north) - 26 wells **17**

1936-1951— "Mudboil areas expanded rapidly; caused Onondaga Creek to become turbid" **18**

1966-76 (spprox.)—Collapses and large vents develop in Tully mudboil area adjacent to Otisco Rd. **36**

1950—Onondaga Creek turbidity noted 2 mi north of Otisco Rd. by local resident. Turbidity in 1950 was seasonal but became year round soon after. **21**

1951—New York State Department of Health report on Onondaga Creek notes high turbidity and suspended materials enters stream south of Cardiff from "springs and potholes." **21**

1952—First mudboil occurrence on Snavlin farm **21**

1953—Sinkholes appear near wells S2 and S5 in East brine field. **36**

1950's—Year-round creek turbidity begins (report by Onondaga Nation). **21**

1954 — Sinkhole appears near well in east brine field. **7**

1955—New York State Department of Health stream survey notes "quicksand pits" near Onondaga Creek tributary T-21, South of Otisco Rd. **21**

1958 — Second mudboil appears at Snavlin farm. **8**

about 1959—Brine company ceases injection of freshwater for salt solutioning. **36**

Late 1950's—West Group wells fully operative; fed by natural ground-water discharge instead of imported water. **34**

Early 1960's—Mudboil activity at Otisco Rd. **21**

1962—Large sinkhole develops in West brine field at well M-18, area settlement continues to early 1980's. **5, 36**

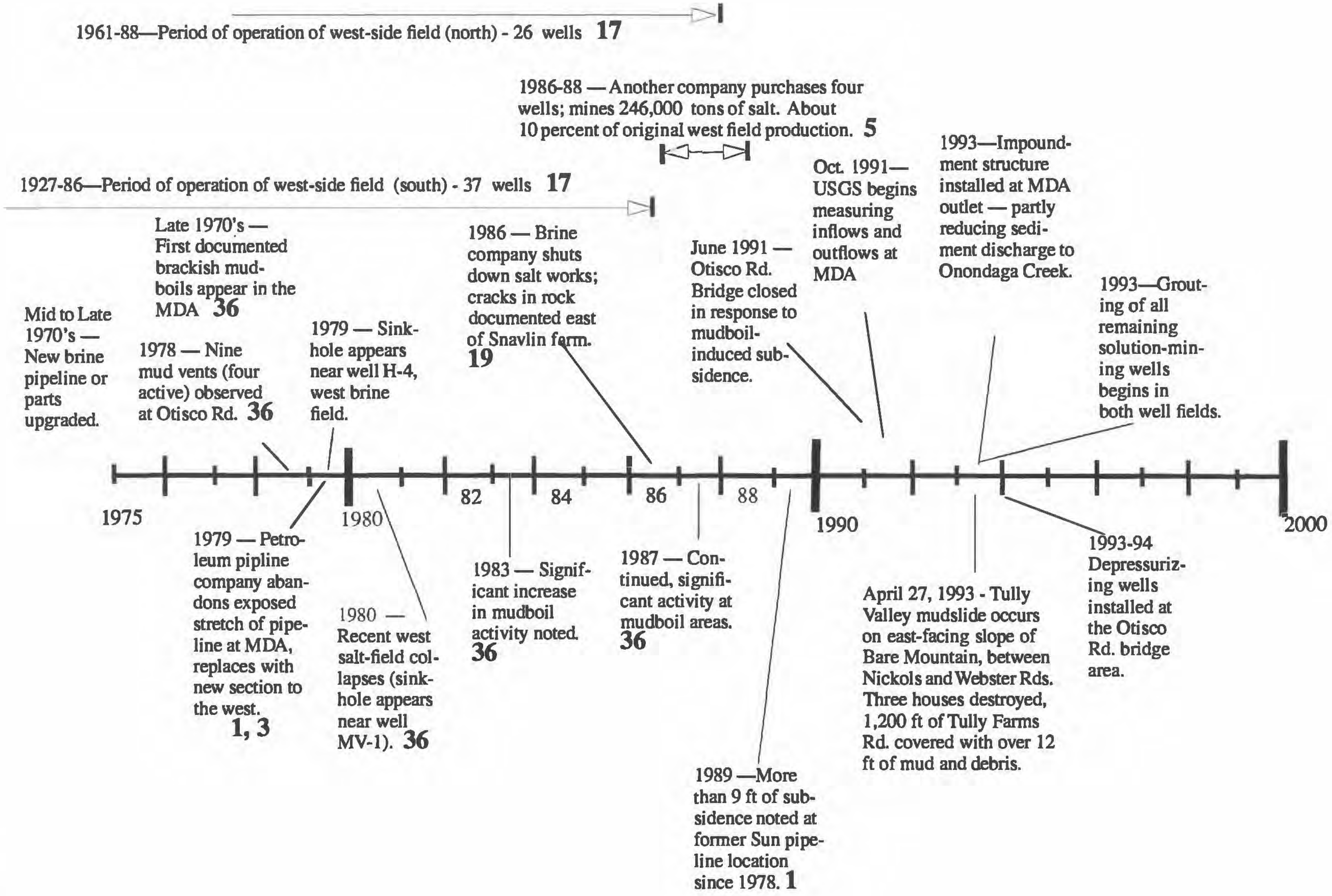
1967—Sun Pipeline exposed at Snavlin Farm (either by subsidence or stream erosion). **8**

1972 (approx.)—Mudboil/subsidence occurrences on Henderson land. Hurricane Agnes exposes Sun pipeline at three locations in Tully Valley. **8**

1974 — Sun pipeline repaired in valley; northernmost repair at King Farm, 1,500 ft south of Otisco Rd. **8**

1975—Salt first noted in 155 ft domestic well at Snavlin farm, five "mud vents" noted at Otisco Rd. **27, 36**

MDA - mudboil / depression area



1961-88—Period of operation of west-side field (north) - 26 wells **17**

1986-88 — Another company purchases four wells; mines 246,000 tons of salt. About 10 percent of original west field production. **5**

1927-86—Period of operation of west-side field (south) - 37 wells **17**

Mid to Late 1970's — New brine pipeline or parts upgraded.

Late 1970's — First documented brackish mudboils appear in the MDA **36**

1978 — Nine mud vents (four active) observed at Otisco Rd. **36**

1979 — Sinkhole appears near well H-4, west brine field.

1979 — Petroleum pipline company abandons exposed stretch of pipeline at MDA, replaces with new section to the west. **1, 3**

1980 — Recent west salt-field collapses (sinkhole appears near well MV-1). **36**

1983 — Significant increase in mudboil activity noted. **36**

1986 — Brine company shuts down salt works; cracks in rock documented east of Snavlin farm. **19**

1987 — Continued, significant activity at mudboil areas. **36**

1989 —More than 9 ft of subsidence noted at former Sun pipeline location since 1978. **1**

June 1991 — Otisco Rd. Bridge closed in response to mudboil-induced subsidence.

Oct. 1991— USGS begins measuring inflows and outflows at MDA

1993—Impoundment structure installed at MDA outlet — partly reducing sediment discharge to Onondaga Creek.

April 27, 1993 - Tully Valley mudslide occurs on east-facing slope of Bare Mountain, between Nickols and Webster Rds. Three houses destroyed, 1,200 ft of Tully Farms Rd. covered with over 12 ft of mud and debris.

1993—Grouting of all remaining solution-mining wells begins in both well fields.

1993-94 Depressurizing wells installed at the Otisco Rd. bridge area.

MDA - mudboil / depression area

APPENDIX 1

TIMELINE REFERENCES

(numbers at left correspond to boldface numbers on timeline)

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APPENDIX 1

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APPENDIX II

TULLY VALLEY WATER-QUALITY DATA 1992-94

[All samples collected by New York State Department of Environmental Conservation—Division of Mineral Resources, analyses by New York State Department of Health - Wadsworth Center Laboratories. mg/L, milligrams per liter; μS/cm, microsiemens per centimeter at degrees Celsius]

Site[1]	Date	Time	pH (Standard Units)	Alkalinity (mg/L as $CaCO_3$)	Specific Conductance (μS/cm)	Chloride, Dissolved (mg/L as CL)	Sulphate, Dissolved (mg/L as SO_4)	Bromide, Dissolved (mg/L as BR)	Iodide, Dissolved (mg/L as I)
Mudboil/Depression Area (MDA)									
MB1	12-9-92	1045	8.11	407	398	37	17	0.2	0.006
MB2	2-4-93	1215	7.31	138	25,900	7,099	863	14	.088
MB2	9-23-93	1115	6.89	128	24,300	4,190	580	13	.085
MB3	12-9-92	1145	7.41	2,150	28,300	2,830	1,889	8.1	.097
MB3	7-8-93	1000	7.61	5,360	3,300	695	73.1	1.5	.019
Features West of Mudboil/Depression Area									
MB4	12-9-92	1230	8.26	255	411	25	25	.6	< .002
MB4	7-8-93	1145	7.84	264	581	13.1	24.2	--	.007
MB5	2-4-93	1030	8.18	241	10,800	2,640	452	4.8	.043
MB5 d	2-4-93	1030	8.48	246	10,800	2,670	454	4.2	.046
MB6	2-4-93	1100	8.03	111	2,560	625	3	2.1	.039
Features Adjacent to Otisco Road									
MB7	12-9-92	1315	8.34	1,900	504	62	16	.8	.006
MB7 d	12-9-92	1315	8.34	1,750	504	62	16	.8	.006
MB7	7-8-93	0900	8.20	222	453	54.5	16.5	.6	.008
MB8	9-23-93	1200	8.42	120	381	49.0	22.3	.6	.005
MB8 d	9-23-93	1200	8.44	118	382	49.3	22.1	.6	.005
Bedrock Well Od-416 Test Zones									
MB9 *	3-9-93	1400	7.36	302	116,000	28,500	2,890	--	.26
MB9 *d	3-9-93	1400	7.24	299	116,000	27,800	2,900	--	.12
MB10	3-9-93	1030	7.28	311	56,100	13,600	1,840	--	.16
MB11 *	3-8-93	1620	6.96	287	196,000	43,600	4,140	--	.37
MB11 *d	3-8-93	1620	7.06	286	195,000	43,500	4,120	--	.36
MB12 *	3-31-93	1300	6.71	215	340,000	67,500	3,170	80	.37
MB12 *d	3-31-93	1300	7.00	210	340,000	67,000	3,240	80	.36
MB13	9-23-93	1530	10.00	41	21,000	5,370	633	15	.068
Tully Valley Landslide									
MS1	7-8-93	1230	7.31	155	32,100	8,260	824	10	.077
MS2	7-8-93	1245	8.14	157	1,490	289	135	1.0	.020
MS2 d	7-8-93	1245	8.15	156	1,490	242	133	1.0	.021
MS3	7-8-93	1300	8.00	134	5,300	1,155	361	3.5	.026

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[1] MB1 = Turbid mudboil in southeast part of MDA.
MB2 = Clear mudboil in central part of MDA.
MB3 = Turbid mudboil in northwest part of MDA.
MB4 = Inflow tributary to the MDA.
MB5 = Water sample from well Od-412, upper bedrock.
MB6 = New mudboil adjacent to well Od-412.
MB7 = Mudboils adjacent to Otisco Road.
MB8 = Otisco Road monitoring well Od-431
MB9 = Bedrock test zone, depth 462 ft.
MB10 = Bedrock test zone, depth 517 ft.
MB11 = Bedrock test zone, depth 608 ft.
MB12 = Bedrock test zone, depth 633 ft.
MB13 = Unconsolidated aquifer, depth 298 ft.
MS1 = South diversion channel at Tully Valley landslide.
MS2 = Freshwater stream at south diversion channel.
MS3 = North diversion channel at Tully Valley landslide.

* Interference from sodium requires sample dilution for Inductively-Coupled Plasma (ICP) analysis, raising ICP minimum reportable values.

d Duplicate sample

APPENDIX II

TULLY VALLEY WATER-QUALITY DATA 1992-94 (cont'd)

[mg/L, milligrams per liter; µg/L, micrograms per liter]

Site	Date	Time	Total Solids (mg/L)	Solids, Residue at 180^0 C Dissolved (mg/L)	Silica, Dissolved Reactive (mg/L as SiO_2)	Sulfide, Dissolved (mg/L as SO_3)	Boron, Dissolved (µg/L as B)	Beryllium, Dissolved (µg/L as Be)	Silver, Dissolved (µg/L as Ag)
Mudboil/Depression Area (MDA)									
MB1	12-9-92	1045	2,610	284	9.8	< 0.2	146	< 4	< 40
MB2	2-4-93	1215	6,940	6,760	11.9	< .2	411	< 4	< 40
MB2	9-23-93	1115	12,600	12,400	13.4	< .2	431	< 4	< 40
MB3	12-9-92	1145	30,200	12,806	11.6	< .2	410	< 1	< 40
MB3	7-8-93	1000	1,800	1,830	8.2	< .2	255	< 1	< 10
Features West of Mudboil/Depression Area									
MB4	12-9-92	1230	288	290	6.2	< .2	51	< 4	< 40
MB4	7-8-93	1145	540	356	8.0	.2	70	< 1	< 10
MB5	2-4-93	1030	3,050	2,800	12.1	64	532	< 4	< 40
MB5 d	2-4-93	1030	3,040	2,820	12.1	72	546	< 4	< 40
MB6	2-4-93	1100	870	686	10.4	.4	250	< 4	< 40
Features Adjacent to Otisco Road									
MB7	12-9-92	1315	18,600	370	8.3	< .2	169	< 4	< 40
MB7 d	12-9-92	1315	19,500	--	8.5	< .2	162	< 4	< 40
MB7	7-8-93	0900	224	284	1.02	< .2	171	< 1	< 10
MB8	9-23-93	1200	387	231	3.57	< .2	195	< 4	< 40
MB8 d	9-23-93	1200	497	243	3.70	< .2	198	< 4	< 40
Bedrock Well Od-416 Test Zones									
MB9 *	3-9-93	1400	57,400	57,500	10.1	80	5,100	< 40	< 400
MB9 *d	3-9-93	1400	57,900	57,600	10.1	160	4,600	<40	< 400
MB10	3-9-93	1030	27,700	27,300	10.5	120	2,600	< 4	< 40
MB11 *	3-8-93	1620	97,500	98,400	10.7	120	7,400	< 40	< 400
MB11 *d	3-8-93	1620	97,600	98,200	10.4	120	7,200	< 40	< 400
MB12 *	3-31-93	1300	170,000	169,000	8.13	44	7,500	< 200	< 2,000
MB12 *d	3-31-93	1300	171,000	170,000	8.35	44	7,400	< 200	< 2,000
MB13	9-23-93	1530	10,800	10,700	5.19	< .2	158	< 4	< 40
Tully Valley Landslide									
MS1	7-8-93	1230	16,600	16,700	9.6	1.4	493	< 1	< 10
MS2	7-8-93	1245	938	1,010	7.6	< .2	107	< 1	< 10
MS2 d	7-8-93	1245	956	1,020	7.5	< .2	111	< 1	< 10
MS3	7-8-93	1300	2,880	2,800	6.6	< .2	329	< 1	< 10

APPENDIX II

TULLY VALLEY WATER-QUALITY DATA 1992-94 (cont'd)

[mg/L, milligrams per liter; µg/L, micrograms per liter]

Site	Date	Time	Barium, Dissolved (µg/L as Ba)	Cadium, Dissolved (µg/L as Cd)	Cobalt, Dissolved (µg/L as Co)	Chromium, Dissolved (µg/L as Cr)	Copper, Dissolved (µg/L as Cu)	Iron, Dissolved (µg/L as Fe)
Mudboil/Depression Area (MDA)								
MB1	12-9-92	1045	119	< 20	< 20	< 20	< 20	< 40
MB2	2-4-93	1215	37	< 20	< 20	< 20	< 20	1,620
MB2	9-23-93	1115	31	< 10	< 20	< 20	< 20	2,300
MB3	12-9-92	1145	510	< 20	< 20	< 20	25	220
MB3	7-8-93	1000	632	< 5	< 5	< 5	< 5	10
Features West of Mudboil/Depression Area								
MB4	12-9-92	1230	71	< 20	< 20	< 20	< 20	< 40
MB4	7-8-93	1145	74	< 5	< 5	< 5	< 5	< 10
MB5	2-4-93	1030	30	< 20	< 20	< 20	< 20	< 40
MB5 d	2-4-93	1030	29	< 20	< 20	< 20	< 20	< 40
MB6	2-4-93	1100	2,790	< 20	< 20	< 20	< 20	73
Features Adjacent to Otisco Road								
MB7	12-9-92	1315	258	< 20	< 20	< 20	< 20	< 40
MB7 d	12-9-92	1315	259	< 20	< 20	< 20	< 20	< 40
MB7	7-8-93	0900	174	< 5	< 5	< 5	< 5	24
MB8	9-23-93	1200	73	< 10	< 20	< 20	< 20	< 40
MB8 d	9-23-93	1200	73	< 10	< 20	< 20	< 20	< 40
Bedrock Well Od-416 Test Zones								
MB9 *	3-9-93	1400	< 200	< 200	< 200	< 200	< 200	< 400
MB9 *d	3-9-93	1400	< 200	< 200	< 200	< 200	< 200	< 400
MB10	3-9-93	1030	< 20	< 20	< 20	< 20	< 20	< 40
MB11 *	3-8-93	1620	< 200	< 200	< 200	< 200	< 200	< 400
MB11 *d	3-8-93	1620	< 200	< 200	< 200	< 200	< 200	< 400
MB12 *	3-31-93	1300	< 1,000	< 1,000	< 1,000	< 1,000	< 1,000	< 2,000
MB12 *d	3-31-93	1300	< 1,000	< 1,000	< 1,000	< 1,000	< 1,000	< 2,000
MB13	9-23-93	1530	89	< 10	< 20	< 20	< 20	< 40
Tully Valley Landslide								
MS1	7-8-93	1230	94	< 5	< 5	< 5	< 5	< 10
MS2	7-8-93	1245	80	< 5	< 5	< 5	< 5	< 10
MS2 d	7-8-93	1245	81	< 5	< 5	< 5	< 5	< 10
MS3	7-8-93	1300	125	< 5	< 5	< 5	10	< 10

APPENDIX II

TULLY VALLEY WATER-QUALITY DATA 1992-94 (cont'd)

[mg/L, milligrams per liter; µg/L, micrograms per liter]

Site	Date	Time	Manganese, Dissolved (µg/L as Mn)	Nickel, Dissolved (µg/L as Ni)	Strontium, Dissolved (µg/L as Sr)	Titanium, Dissolved (µg/L as Ti)	Vanadium, Dissolved (µg/L as V)	Zinc, Dissolved (µg/L as Zn)
Mudboil/Depression Area (MDA)								
MB1	12-9-92	1045	67	< 20	7,050	< 20	< 20	< 40
MB2	2-4-93	1215	88	< 20	74,000	< 20	< 20	< 40
MB2	9-23-93	1115	93	< 20	73,800	< 20	< 20	< 40
MB3	12-9-92	1145	201	< 20	69,500	< 20	< 20	< 40
MB3	7-8-93	1000	104	< 5	20,200	< 5	< 5	< 10
Features West of Mudboil/Depression Area								
MB4	12-9-92	1230	58	20	375	< 20	< 20	< 40
MB4	7-8-93	1145	29	< 5	445	< 5	< 5	12
MB5	2-4-93	1030	222	< 20	55,700	< 20	< 20	< 40
MB5d	2-4-93	1030	222	< 20	56,400	< 20	< 20	< 40
MB6	2-4-93	1100	23	< 20	56,200	< 20	< 20	< 40
Features Adjacent to Otisco Road								
MB7	12-9-92	1315	< 20	< 20	10,600	< 20	< 20	< 40
MB7 d	12-9-92	1315	< 20	< 20	10,600	< 20	< 20	< 40
MB7	7-8-93	0900	17	< 5	11,500	< 5	< 5	< 10
MB8	9-23-93	1200	59	< 20	10,600	< 20	< 20	< 40
MB8 d	9-23-93	1200	61	< 20	10,600	< 20	< 20	< 40
Bedrock Well Od-416 Test Zones								
MB9 *	3-9-93	1400	< 200	< 200	32,200	< 200	< 200	< 400
MB9 *d	3-9-93	1400	< 200	< 200	31,400	< 200	< 200	< 400
MB10	3-9-93	1030	94	< 20	21,300	< 20	< 20	< 40
MB11 *	3-8-93	1620	< 200	< 200	39,600	< 200	< 200	< 400
MB11 *d	3-8-93	1620	< 200	< 200	39,100	< 200	< 200	< 400
MB12 *	3-31-93	1300	< 1,000	< 1,000	56,100	< 1,000	< 1,000	< 2,000
MB12 *d	3-31-93	1300	< 1,000	< 1,000	56,000	< 1,000	< 1,000	< 2,000
MB13	9-23-93	1530	< 20	< 20	125,000	< 20	< 20	< 40
Tully Valley Landslide								
MS1	7-8-93	1230	529	< 5	31,600	< 5	< 5	< 10
MS2	7-8-93	1245	10	< 5	1,930	< 5	< 5	41
MS2 d	7-8-93	1245	10	< 5	1,930	< 5	< 5	41
MS3	7-8-93	1300	480	< 5	4,020	< 5	< 5	101

TULLY VALLEY WATER-QUALITY DATA 1992-94 (cont'd)

[mg/L, milligrams per liter; µg/L, micrograms per liter]

Site	Date	Time	Molybdenum, Dissolved (µg/L as Mo)	Lead, Dissolved (µg/L as Pb)	Antimony, Dissolved (µg/L as Sb)	Tin, Dissolved (µg/L as Sn)	Thallium, Dissolved (µg/L asTl)	Aluminum, Dissolved (µg/L as Al)
Mudboil/Depression Area (MDA)								
MB1	12-9-92	1045	< 80	< 80	< 300	< 200	< 300	< 400
MB2	2-4-93	1215	< 80	< 80	< 300	< 200	< 300	< 400
MB2	9-23-93	1115	< 80	< 80	< 300	< 200	< 300	< 400
MB3	12-9-92	1145	< 80	< 80	< 300	< 200	< 300	< 400
MB3	7-8-93	1000	< 20	< 20	< 80	< 50	< 80	< 100
Features West of Mudboil/Depression Area								
MB4	12-9-92	1230	< 80	< 80	< 300	< 200	< 300	< 400
MB4	7-8-93	1145	< 20	< 20	< 80	< 50	< 80	< 100
MB5	2-4-93	1030	< 80	< 80	< 300	< 200	< 300	< 400
MB5 d	2-4-93	1030	< 80	< 80	< 300	< 200	< 300	< 400
MB6	2-4-93	1100	< 80	< 80	< 300	< 200	< 300	< 400
Features Adjacent to Otisco Road								
MB7	12-9-92	1315	< 80	< 80	< 300	< 200	< 300	< 400
MB7 d	12-9-92	1315	< 80	< 80	< 300	< 200	< 300	< 400
MB7	7-8-93	0900	< 20	< 20	< 80	< 50	< 80	< 100
MB8	9-23-93	1200	< 80	< 80	< 300	< 200	< 300	< 400
MB8 d	9-23-93	1200	< 80	< 80	< 300	< 200	< 300	< 400
Bedrock Well Od-416 Test Zones								
MB9 *	3-9-93	1400	< 800	< 800	< 3,000	< 2,000	< 3,000	< 4,000
MB9 *d	3-9-93	1400	< 800	< 800	< 3,000	< 2,000	< 3,000	< 4,000
MB10	3-9-93	1030	< 80	< 80	< 300	< 200	< 300	< 400
MB11 *	3-8-93	1620	< 800	< 800	< 3,000	< 2,000	< 3,000	< 4,000
MB11 *d	3-8-93	1620	< 800	< 800	< 3,000	< 2,000	< 3,000	< 4,000
MB12 *	3-31-93	1300	< 4,000	< 4,000	< 15,000	< 10,000	< 15,000	< 20,000
MB12 *d	3-31-93	1300	< 4,000	< 4,000	< 15,000	< 10,000	< 15,000	< 20,000
MB13	9-23-93	1530	< 80	< 80	< 300	< 200	< 300	< 400
Tully Valley Landslide								
MS1	7-8-93	1230	< 20	< 20	< 80	< 50	< 80	< 100
MS2	7-8-93	1245	< 20	< 20	< 80	< 50	< 80	< 100
MS2 d	7-8-93	1245	< 20	< 20	< 80	< 50	< 80	< 100
MS3	7-8-93	1300	< 20	< 20	< 80	< 50	< 80	< 100

APPENDIX II

TULLY VALLEY WATER-QUALITY DATA 1992-94 (cont'd)

[µg/L, micrograms per liter; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25° C; pci/L, picocuries per liter]

Site	Date	Time	Calcium, Dissolved (µg/L as Ca)	Potassium, Dissolved (µg/L as K)	Magnesium, Dissolved (µg/L as Mg)	Sodium, Dissolved (µg/L as Na)	Tritium (pci/L)	Tritium (pci/L)/(3.2) (Tritium Units)
Mudboil/Depression Area (MDA)								
MB1	12-9-92	1045	14.8	< 2	8.1	47.0	< 9	< 2.81
MB2	2-4-93	1215	378	10.7	195	4,040	50.2 ± 8.9	15.7 ± 2.8
MB2	9-23-93	1115	364	10.5	178	3,530	45.1±16.1	14.1±5.0
MB3	12-9-92	1145	333	11.7	182	4,370	39. ± .9.	12.2 ± 2.8
MB3	7-8-93	1000	125	2.6	44.5	344	< 11.2	< 3.2
MB3	9-23-93	1245	--	--	--	--	46.0 ± 21.0	14.4 ± 6.56
Features West of Mudboil/Depression Area								
MB4	12-9-92	1230	103	2.9	19.0	8.2	75 ± 12	23.4 ± 3.75
MB4	7-8-93	1145	94.2	2.4	16.7	8.4	65.7 ± 15.	20.5 ± 4.69
MB5	2-4-93	1030	220	8.6	119	1,570	48.1±7.26	15.± 2.27
MB5 d	2-4-93	1030	220	8.0	119	1,590	38.1±6.86	11.9 ± 2.27
MB6	2-4-93	1100	78.9	2.4	50.4	267	< 7.40	< 2.19
Features Adjacent to Otisco Road								
MB7	12-9-92	1315	16.6	< 2	7.9	55.3	< 9.0	< 2.81
MB7 d	12-9-92	1315	16.8	< 2	8.0	56.1	--	--
MB7	7-8-93	0900	16.5	1.0	8.0	50.9	< 12.3	< 3.84
MB8	9-23-93	1200	12.3	< 2	6.1	54.9	< 16.4	< 5.12
MB8 d	9-23-93	1200	12.2	< 2	6.0	55.1	< 19.6	< 6.12
Bedrock Well Od-416 Test Zones								
MB9 *	3-9-93	1400	1,470	77.1	201	19.000	74.8±15.8	23.4 ± 4.94
MB9 *d	3-9-93	1400	1,440	79.5	197	19,000	95.5 ± 21.	29.8 ± 9.31
MB10	3-9-93	1030	920	42.3	156	8,430	81.1±17.2	25.3 ± 5.38
MB11 *	3-8-93	1620	2,120	124	238	33,000	97.9±15.8	30.6 ± 4.94
MB11 *d	3-8-93	1620	2,090	118	236	34.100	--	--
MB12 *	3-31-93	1300	2,430	195	313	59,200	51 ± 20.3	15.9 ± 6.34
MB12 *d	3-31-93	1300	2,430	218	313	57,800	57.5±16.4	18. ± 5.12
MB13	9-23-93	1530	409	15.9	125	3,030	19.6±16.4	6.12 ± 5.12
Tully Valley Landslide								
MS1	7-8-93	1230	700	18.2	218	4,630	42.5±22.2	13.3 ± 6.94
MS2	7-8-93	1245	126	1.9	26.1	131	60.8±17.0	19 ± 5.31
MS2 d	7-8-93	1245	125	2.0	26.1	130	--	--
MS3	7-8-93	1300	155	5.6	40.1	721	43.6±17.0	13.6 ± 5.31
MS4	9-23-93	1430	--	--	--	--	24.7±16.2	7.71± 5.06