Investigation of the 1993 Tully Valley Landslide

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Introduction

On April 27, 1993; a large landslide occurred in Tully Valley, in the town of Lafayette, NY (Photo 1). From the base of the east facing slope of Bare Mountain, the slide extended some 0.8 km into the center of Tully Valley. The landslide back scarp is about 400 m long and runs parallel to the north-south aligned valley centerline. Large portions of farm land slumped and displaced. A spread of reddish mud flow covered wide areas of the slide front. A 340 m section of Tully Farms Road was covered by up to 5 m of debris. The volume of displaced soil is in the order of 0.5 million cubic meters. The earth movement lasted about 30 minutes and the slide is believed to be the largest to have occurred in New York State in over 75 years. While there was no loss of life, the property damage included the loss of three homes and about 10 hectares of farm land (Fickies, 1993; Kappel et al, 1996). Following the landslide, several springs developed in the back area of the slide basin. The slide debris over Tully Farms Road was later removed. The near vertical back slope face has now re-graded with subsequent sloughing and talus accumulation. An account of an investigation to identify the nature and possible causes for the 1993 Tully Valley Landslide is given in this paper.

Tully Valley

Tully Valley is located at the foot of the northern edge of the Appalachian Uplands within Onondaga County in Central New York, approximately 20 km south of Syracuse, Fig. 1. Tully Valley is at the southern end of the Onondaga Trough which begins from the Valley Heads Moraine near the town of Tully to the south and extends north toward Onondaga Lake and Syracuse. The U shaped valley floor is about 1.5 km wide. Onondaga Creek flows north along the center of the valley and drains into Onondaga Lake. Tully Valley is sparsely populated and the land use is primarily residential and semi agricultural.

There is suggestive evidence of previous landslide activity in Tully Valley. Three locations of past sliding along the same west side of the valley but to the north of the recent slide are shown in Figure 1. The closest of these earlier slides is only 70 m north of the 1993 slide, and is estimated to have occurred more than 150 years ago (Kappel et al, 1996). Judging by their location and shape, these three previous slides and the recent 1993 slide may have been caused by a similar mechanism. Segments of undisturbed topography that may be susceptible to slide hazard presently exist between these previous slide sites. Other much older slide features have been identified in and around the general vicinity of Tully Valley. These latter prehistoric slides are believed to have been a result of rapid lowering of Pliestocene lakes (Jäeger and Wieczorek, 1994).

From 1889 to 1988, there was intensive salt solution-mining at the south end of Tully Valley about 5 km south of the 1993 Landslide. Deep wells were drilled into salt beds within the Syracuse Formation at depths below 300 m. Fresh water from the nearby Tully Lakes was injected into the deep wells to return as brine through recovery wells. An estimated 90 million metric tons of salt was removed by solution mining (Walker and Mahoney, 1993). The mining process resulted in large scale dissolution and subsidence of up to 15 m over an area of about 2 square kilometers (Kappel et al, 1996). Soon after operation of the brine fields ended in 1988, a groundwater level rise in excess of 20 m was noted at an observation well located more than a kilometer from the extraction site. In subsequent years, the seasonal variation of groundwater levels at this observation well was less than 5 m. Solution mining operations in Tully Valley have altered the groundwater levels and quality within the valley (Getchell, 1983, Rubin et al, 1991, Perkins and Romanowicz, 1996, Kappel et al, 1996). The extent of groundwater level and quality change that may have occurred at the 1993 slide site following the secession of brine mining operations in Tully Valley is not well known.

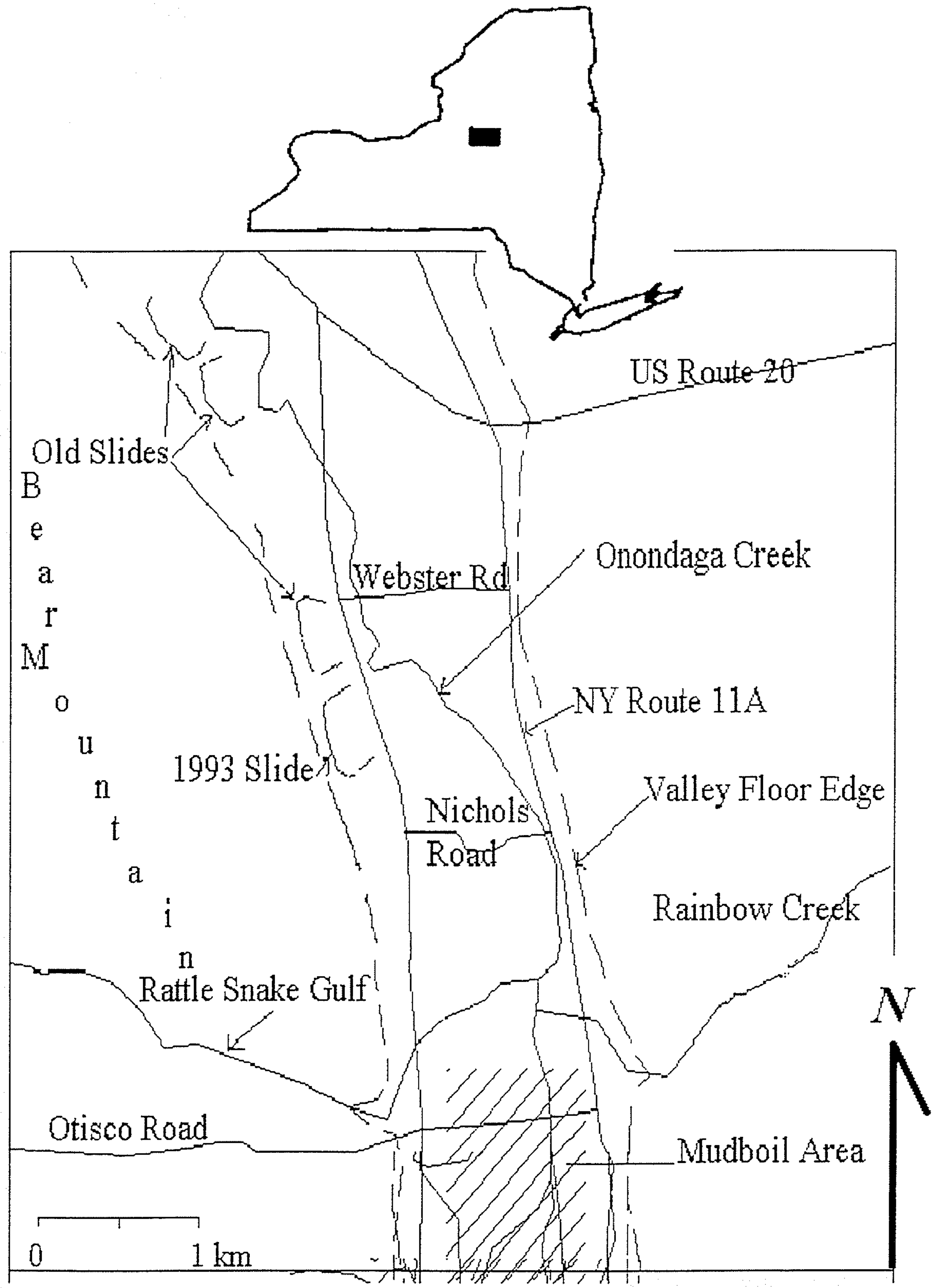


Figure 1 - Tully Valley location and features.

Mudboils were first noted in Tully Valley in 1899, ten years after the start of brine mining operations. Mudboils are volcano-like structures of up to 10 m in diameter that discharge water and fine-grained sediments. The ground surface around a mudboil subsides as sediment is removed from depth. At present, mudboil activity continues at the center of Tully Valley some 2 km south of the 1993 landslide (Figure 1) and resulted in the collapse of the Otisco Road bridge in 1991. Water quality associated with the mudboils range between turbid to clear and fresh to brackish and discharge levels tend to vary seasonally both in quality and quantity (Kappel et al, 1996). Mudboils have developed to a much lesser extent elsewhere and in the 1993 landslide basin.

Geology

The predominant bedrock sequence in Tully Valley consists of shales and limestones that range from late Silurian to middle Devonian age (Getchell, 1983, Kappel et al, 1996). At the slide site (Figure 2), Hamilton Group Shales form the lower part of Bare Mountain and extend below land surface. The Hamilton Group Shales are followed by Onondaga Limestone over Oriskany Sandstone. Below the Oriskany Sandstone lie the Helderberg Group of limestone and dolostone sequence over the Salina Group shale, dolostone and salt beds. Glacial scour at the center of the valley probably extends close to the base of the Helderberg Group and cuts through distinct water bearing bedrock zones including the Oriskany Sandstone and the Onondaga Limestone contacts. The general dip of the bedrock units is to the south at 8 to 16 m per km (Kappel et al, 1996). There are also two major joint sets that have strikes of N8°W and N80°E and dip of 87°W and 88°S, respectively (DeGroff, 1950, Getchell and Muller, 1992). A major fracture set runs through the upper east slope of Bare Mountain at an approximately parallel alignment to the joint strike of N8°W (Kappel et al, 1996). Both the fracture and joint are in line with and may extend to pass through the abandoned brine field at the southern end of the valley.

The thickness of surficial deposits in the valley have been estimated at 120 to 150 m (Faltyn, 1957, Kantrowitz, 1970) and are largely the result of Wisconsin glaciation (Muller, 1964). Glacial activity within the valley resulted in surficial deposits that range from lodgment till along the valley sides and base, fluvial outwash deposits of stratified sand and gravel sequences, and massive thick lacustrine silt and clay units deposited within proglacial lakes. The most prominent post-glacial feature in the valley is the Tully Moraine, a large deposit of mixed drift which seals off the southern end of the Onondaga Trough. The Tully Moraine is part of the Valley Heads Moraine and marks the furthest advance of the Wisconsin ice sheet (Muller, 1964). The massive red lacustrine silty clay unit exists throughout the northern Fingerlakes region of Central New York and is believed to be a proglacial sediment derived from the Vernon Shale of the Salina Group (Blagborough, 1951).

The sand and gravel, mixed drift soil acquifers of Tully Valley are separated by till, glaciolacustrine clay and silt deposits (Getchell and Muller, 1992). As is the case with surface water in Tully Valley, groundwater flows to the north at intermediate and regional scales. Regional scale flow originates from recharge areas in the Appalachian Upland and moves primarily through bedrock aquifers. The Tully Moraine is a source of intermediate scale flow which moves at or near the bedrock-soil interface. Local groundwater flow originates from the valley sides and flows toward the center of the valley recharging the valley surface deposits that act as unconfined aquifers.

Field Investigation

A field investigation program was started in 1995 to define the soil and ground water conditions and identify the probable factors responsible for the 1993 landslide. The landslide area together with locations of boreholes drilled during the field investigation and of natural springs sampled for laboratory testing are shown in Figure 3. Soil samples were recovered from boreholes for laboratory testing and detailed classification. Insitu vane shear strength tests were performed at various depths within the clay soil strata. X-ray diffraction analyses were conducted on clay samples to determine the clay mineral composition. Consolidated undrained triaxial, strain rate controlled consolidation, lab vane shear and Atterberg limit tests were performed on clay samples. Standard penetration testing and split spoon sampling was carried out in the coarse soil formations. Where bedrock was encountered, core samples were obtained for classification and assessment of rock quality. Piezometers and slope indicator casings

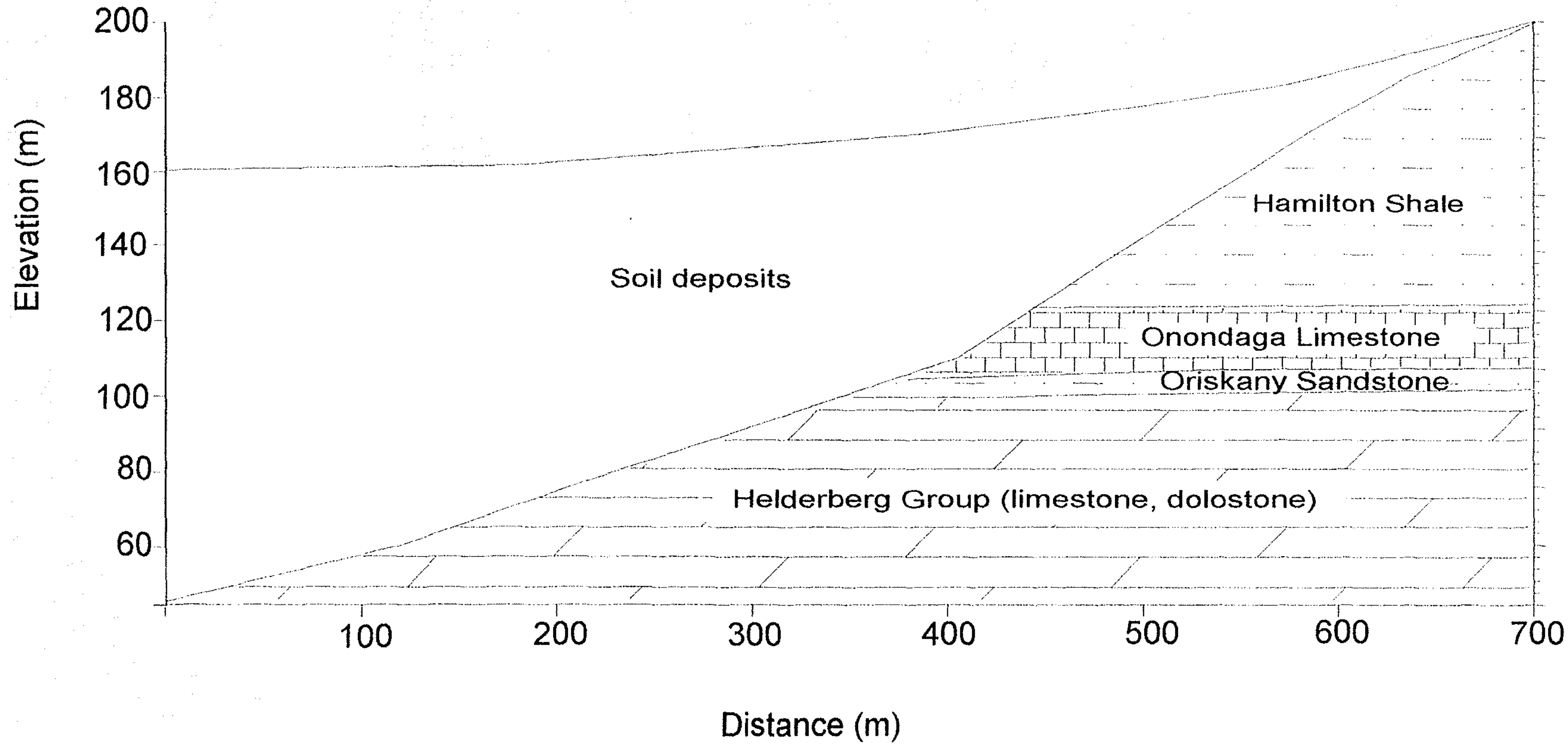


Figure 2 - Bedrock strata at the 1993 Tully Valley Slide

were installed in boreholes for long term monitoring of groundwater pressures and slope movement. Information on depths, elevations and sensors installed in boreholes is summarized in Table 1. A tipping bucket rain gage and ambient temperature sensors have also been installed to record site specific meteorological data. Water samples were collected between January and May 1996 from springs within the slide basin, boreholes and a water well for assessment of temporal and spatial variation of water quality. Temperature and dissolved oxygen measurements were made in the field. Specific conductivity, pH and ion concentrations were determined in the laboratory. More detailed accounts of the geotechnical and water quality investigations will be reported elsewhere (Burgmeier, 1997, Curran, 1997).

Pre-Slide Stratigraphy

A reconstructed cross section of the pre-slide soil stratigraphy is shown in Figure 4. The section was developed from pre-slide topographic contours and borehole records along the north and south edges of the slide as well as within the slide and from the stratigraphy exposed at the back scarp in 1993. The slope of the gently inclined ground surface is about 8°. The red silty clay thins out towards the valley wall. A wedge of sand and gravel resting on the inclined bedrock surface interfingers into the clay layer. The sand and gravel wedge is connected to a varved clay sequence that underlies the massive red clay unit. The varved clay overlies an inclined bed of till like silty sand and gravel. Brown-gray silty clay over fine sand underlies the varved clay and rests on the bedrock floor. In borehole 7, black non-calcareous shale was encountered at elevation 178 m and a depth of 6.3 m below surface. The shale sample is likely a Cardiff Member. Within the slide basin and in borehole 6, dark gray calcareous shale was encountered at elevation 127 m and depth of 39 m below surface. This shale sample is likely a Union Springs member. Both the Cardiff and Union Springs belong to the Marcellous Formation of the Hamilton Group (Grasso, 1966). The top 2 to 5 m depth of both shale units is fractured.

Precipitation and Groundwater Pressure

The long term average seasonal snowfall for the Syracuse area is 2,800 mm. A record total of 4,880 mm of snow fell in the Syracuse area in the 1992-93 season. The snowfall of 561 mm on March 13, 1993 and the total for the month of 1381 mm are also records. There was also additional snowfall of 309 mm in April. The long term precipitation data for the general area is based on weather observations at Syracuse Airport. There was an unusual depth and duration of snow cover in March and April of 1993. However, the water equivalent precipitation for the year (1110 mm) as well as for March (95 mm) and April (166 mm), were above average but have been exceeded in previous years, as in 1976. Selected piezometric observations, Figure 5, indicate seasonal groundwater level changes in the red silty clay are small but more marked changes occur within the coarse strata and in fractured bedrock zones located close to ground surface. Generally, groundwater pressures are lowest in late Summer to early Fall and highest in late winter to early Spring.

Slide Basin Water Quality

The water quality of springs, the locations of which is shown in Figure 3, in the slide basin has been variable. Specific conductance and chemical concentrations varied over a large range throughout the slide area. Springs nearest the face of the landslide scarp and at upper elevations had low total dissolved solids (TDS), with conductivities around 400 mmhos/cm. Springs farther away from the scarp face, toward the center of the slide area, had much higher TDS with specific conductivity values approaching 50,000 mmhos/cm. Water from boreholes varied in TDS according to depth and location, but all borehole samples had TDS ranging from 200 to 1,000 ppm. Brackish and slightly brackish water samples had a strong hydrogen sulfide odor. In general, brackish springs decreased in TDS and specific conductance from April to May. During the winter months, the diluting effect of precipitation and local recharge on the water chemistry was minimal. Piper plots for brackish spring water in the landslide basin, Salina brine as well as brackish mudboil water and bedrock water samples from Deep Well On-416 in the mudboil area are shown in Figure 6. The data for the mudboil sources is scattered. The other three sources show very similar composition. However, the concentrations are highest for the Salina brine followed by the deep

Table 1: Borehole installation summary

BH #	Depth (m)	Elevation (m)	Installation(s)	Completion Date	Comments
1a	4.9	165.8	SP @4.6m	10/29/95	adjacent to BH #1b
1b	30.8	165.8	SI to 30.8m	10/28/95	bentonite plugs; cement backfill; adjacent to BH #1a
2	29.6	177.7	SP @4.6m SP @15.7m PP @16.2m PP @21.9m	10/25/95	VWP and datalogger installed June 21,1996 rainfall gauge location
3	17.2	192.6	SP @7.6m PP @14.0m	10/26/95	bentonite plug above PP; hole terminates in till
4	15.7	193.2	SP @7.5m SP @15.5m	11/8/95	VWP and datalogger installed May 30,1996 hole is located above headscarp
5	16.5	194.5	SI to 16.5m	11/9/95	hole is located above headscarp ; cement backfill
6	39.3	166.1	VWP @7.8m VWP @14.1m VWP @38.3m	10/10/96	hole in center of slide basin VWP and datalogger equipped bedrock @38.3m
7	7.6	184.1	SP @7.0m	10/16/95	VWP and datalogger installed October 19, 1996 ; bedrock @6.1m
8a	29.3	171.9	PP @29.3m	10/11/95	backfilled with bentonite plug and clay cuttings; adjacent to BH #8c
8b	19.8	174.7	SI to 19.4m	10/17/95	cement backfill
8c	11.6	171.9	SP @3.7m PP @11.6m	10/12/95	no sampling; adjacent to BH #8a backfilled with bentonite plug and sand
9a	14.6	164.9	PP @14.6m	10/12/95	no sampling; adjacent to BH #9 ; backfilled with clay cuttings
9b	16.9	164.9	PP @10.7m	10/10/95	adjacent to BH #9; backfilled with clay cuttings

PP - pneumatic piezometer

SP - stand pipe

SI - slope indicator casing

VWP - vibrating wire piezometer

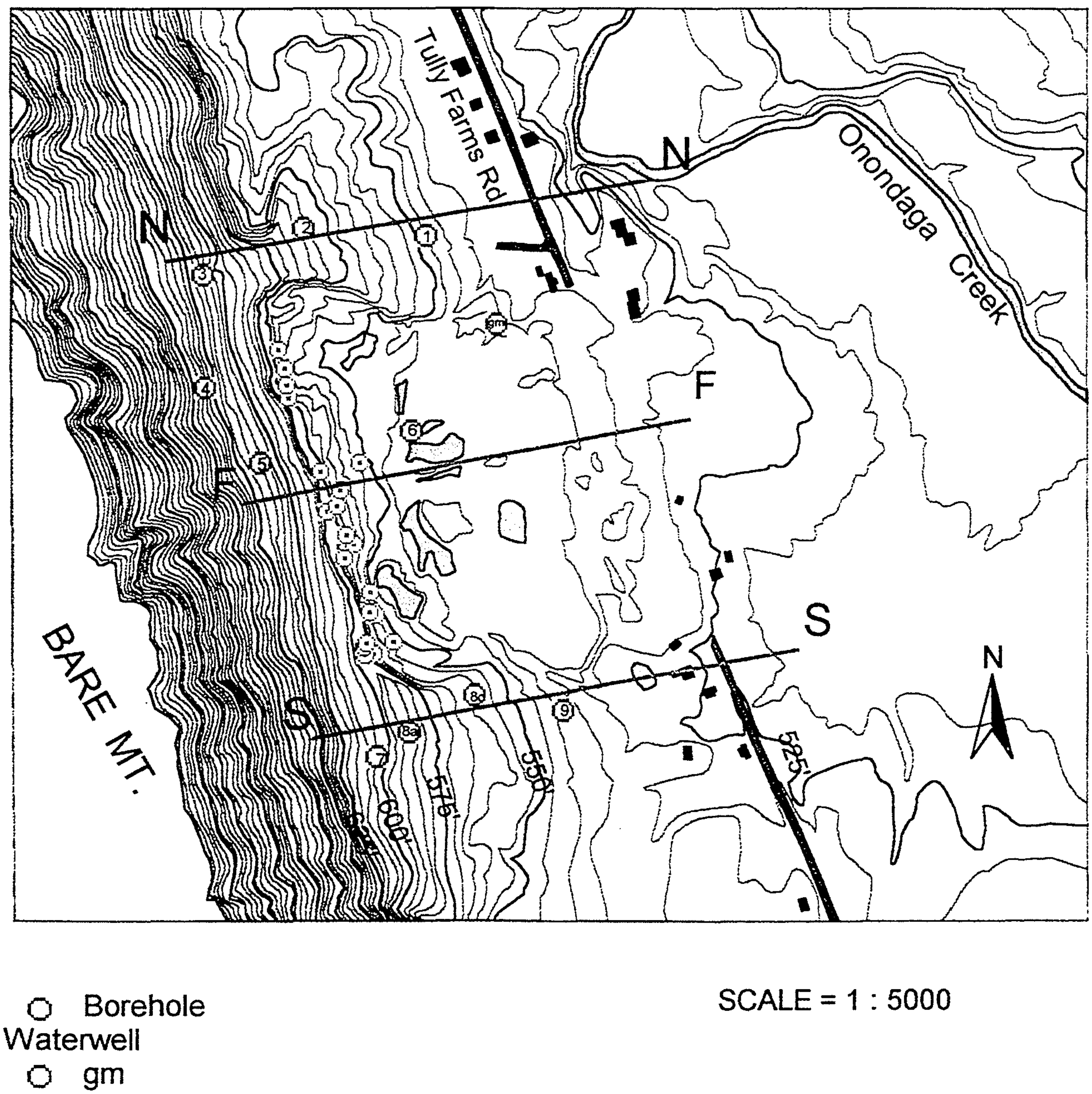


Figure 3 - The 1993 Tully Valley Slide area and locations of boreholes and springs.

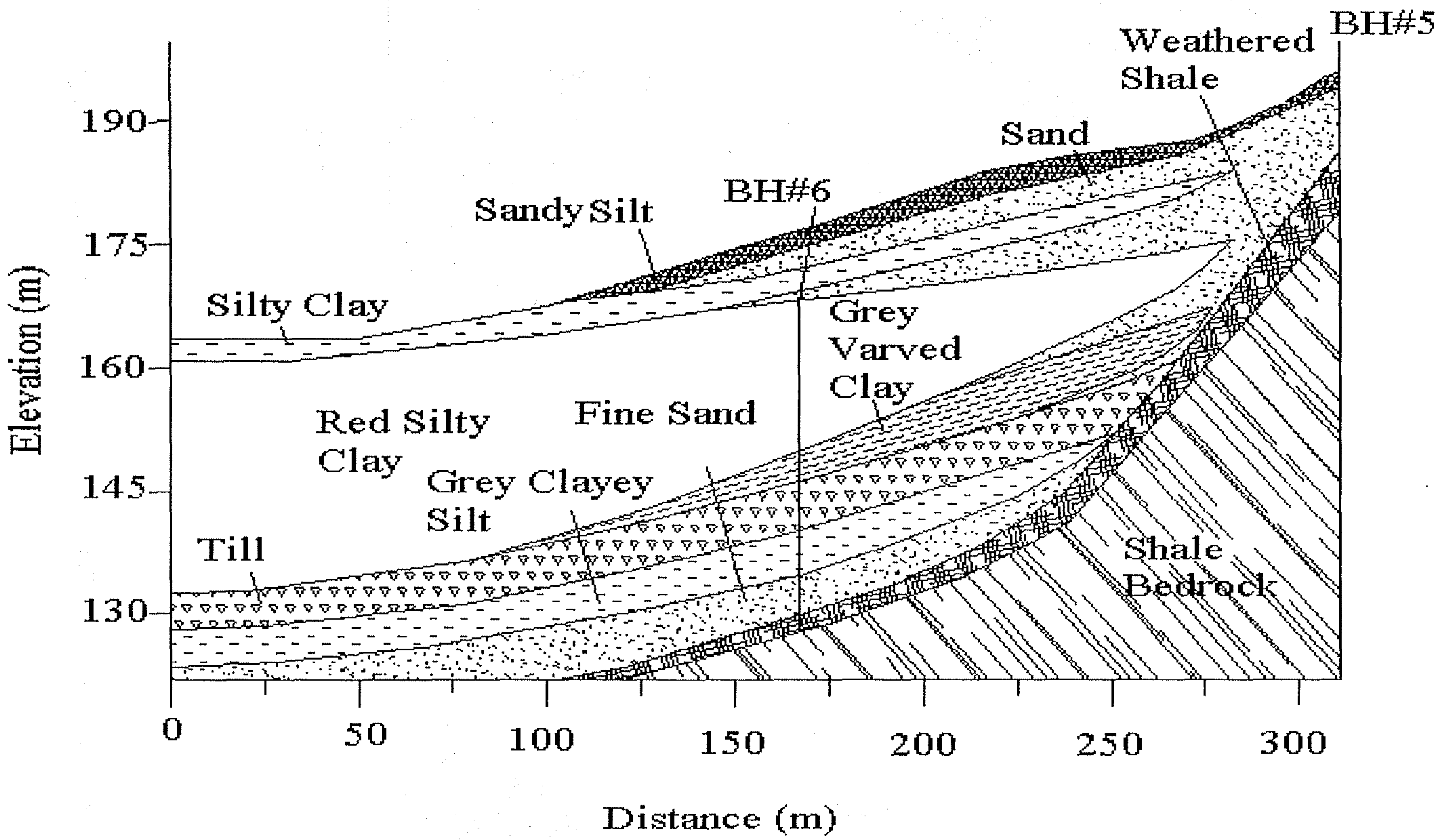


Figure 4 - A reconstructed pre-failure section of the 1993 Tully Valley Slide.

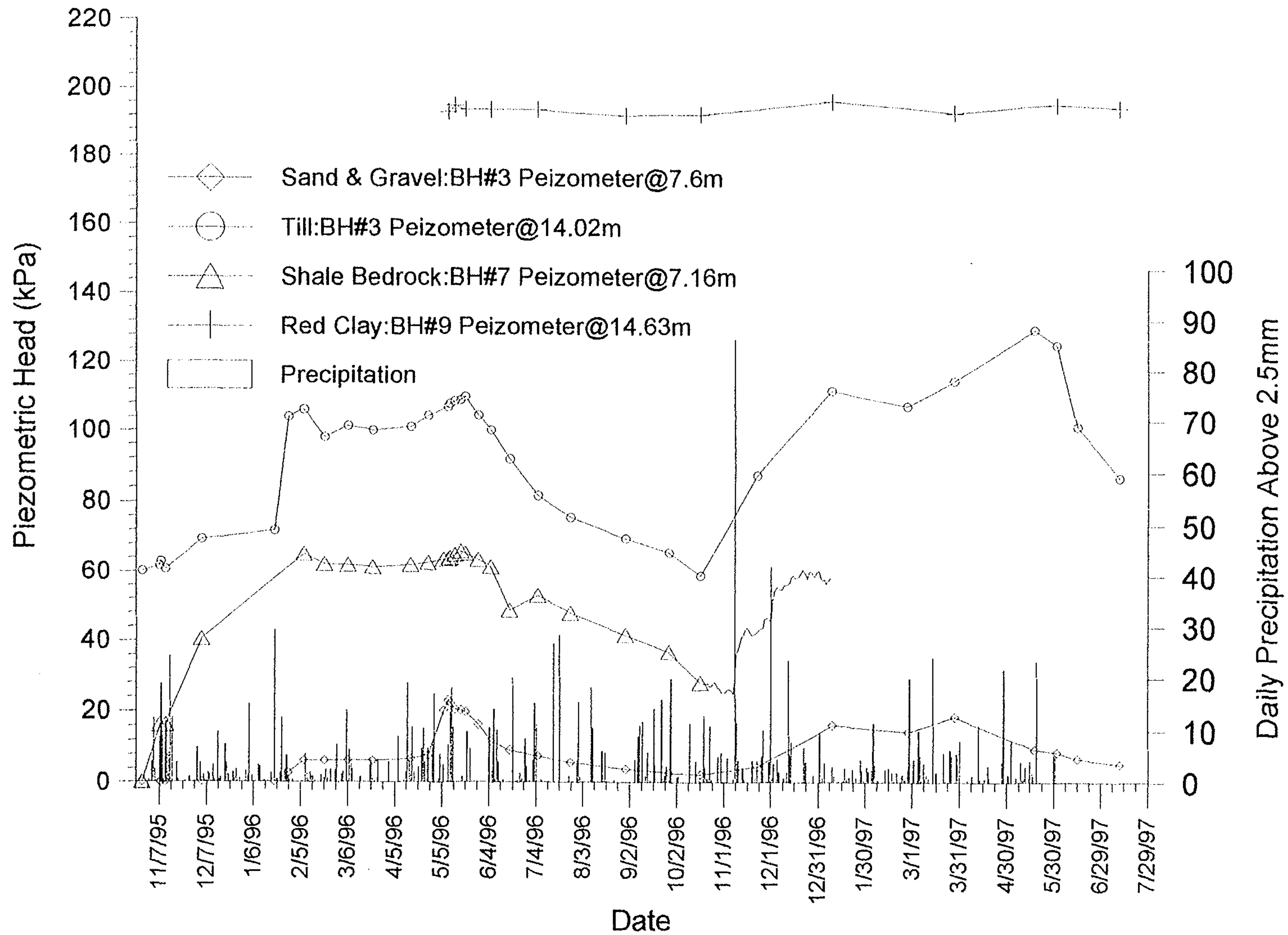


Figure 5 - Changes in groundwater pressure with time in different strata and daily precipitation record for the Syracuse area.

Figure 6a: Brackish Springs

No.	TDS	Source
1	14,600	spring 5
2	22,100	spring 6
3	9,700	spring 7
4	19,100	spring 13
5	38,800	spring 14
6	22,900	spring 15
7	13,500	spring 16

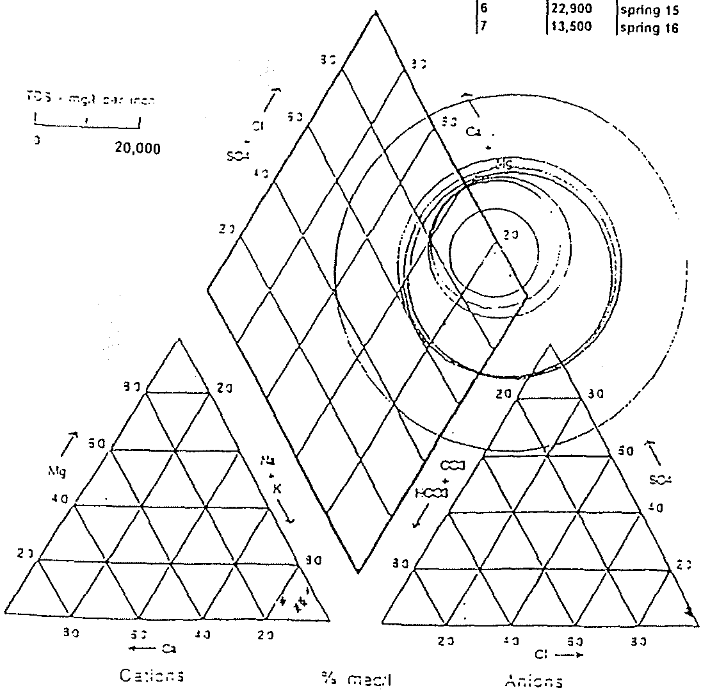


Figure 6b: Salina Salt Unit (Nobel, 1993)

No	TDS	Well Name
1	251345	USGS-1
2	81020	5305(MV-
3	96967	G174(MV-
4	299379	G175(RX-
5	83733	C234(MV-
6	1238	5303(H-7)
7	1390	C233(H-7)
8	5945	6673(RX-
9	14324	6672(N-1)

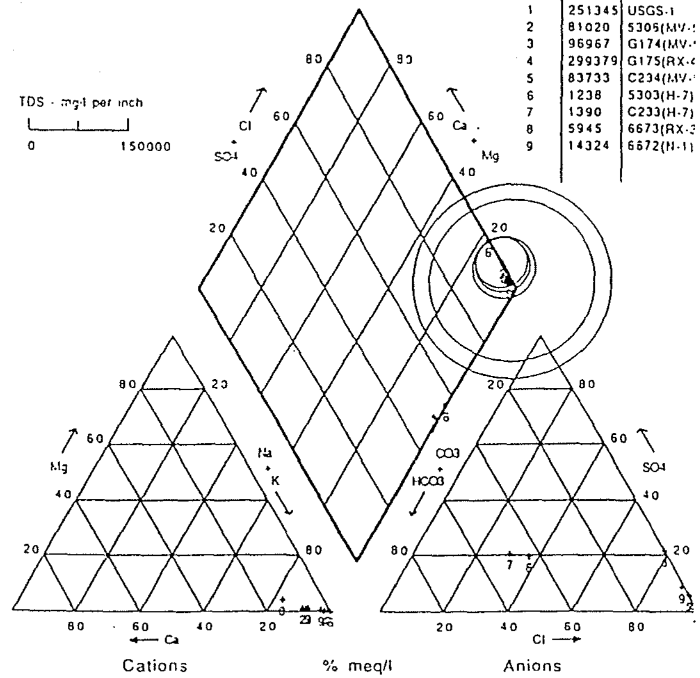


Figure 6c: Mudboils (Kappel, et al 1996)

No.	TDS	Source
1	284	MB1
2	6,760	MB2
3	12,800	MB3
4	290	MB4
5	2,800	MB5
6	686	MB6
7	370	MB7

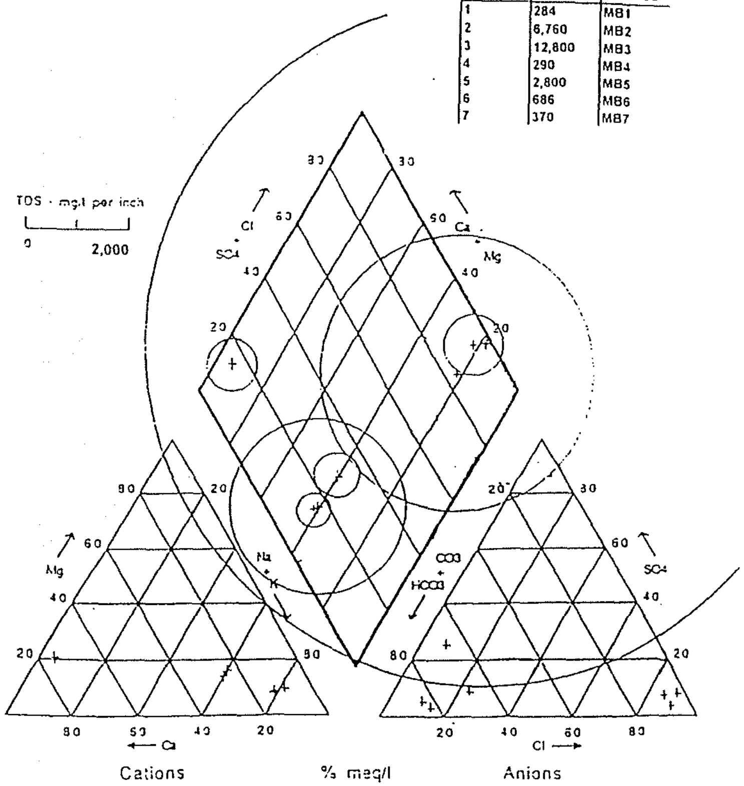
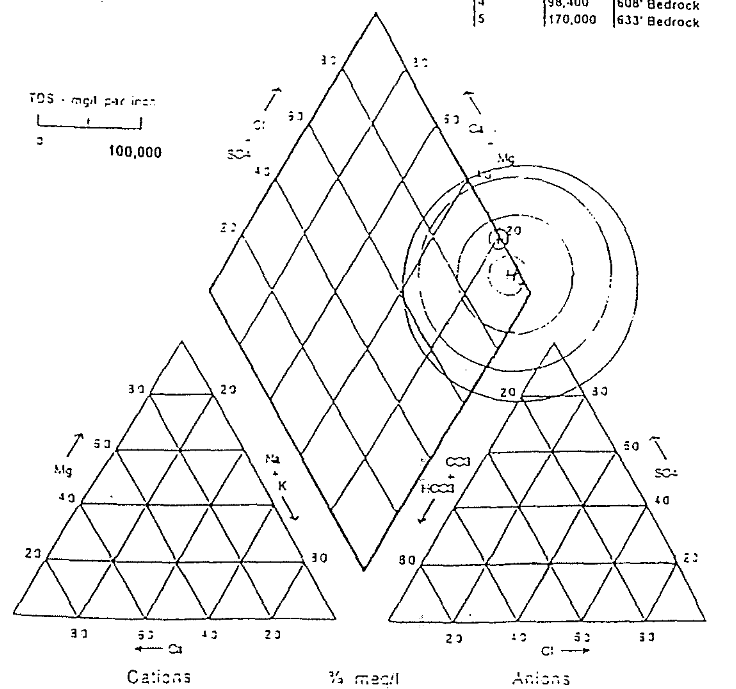


Figure 6d: Deep Well, On-416 (Kappel, et al 1996)

No.	TDS	Source
1	10,800	298' unconsolidated
2	57,500	462' Bedrock
3	27,700	517' Bedrock
4	98,400	608' Bedrock
5	170,000	633' Bedrock



well, slide area and mudboil sources. This suggests some of the slide area springs encounter much less dilution as compared to water samples in the mudboil depression. Bivariate plots for sulfate and chloride concentrations in the slide area brackish water samples show two distinct mixing lines, Figure 7. The Salina evaporites are the probable sole sources for the chlorides and the separation of the mixing lines may therefore be due to different sulfate sources. Gypsum in the Salina evaporites is one source while the second likely source is the Chittenango shale. Of the four shale units in the Marcellus Formation of the Hamilton Group, the Chittenango is the only unit that contains abundant pyrites (Grasso, 1966). Thus in passing through fractures in the Chittenango shale, water emanating from some of the brackish springs may be picking up additional sulfates. Comparatively, sulfate concentrations are an order of magnitude less than chloride concentrations. If the two sulfate source hypotheses holds, it appears the contributions from the two sources are comparable. These observations do not resolve the question as to whether the salt source is local or linked to the brine fields. The effect of noted changes in groundwater quality on the red clay behavior have not been explored. However, previous findings suggest the infusion of dissolved solids in the clay structure by cation exchange would tend to improve the strength behavior (Di Maio, 1996).

Red Silty Clay

Index properties of the red silty clay were determined based on samples obtained from the slide exposure and debris on 4/29/93 as well as on samples recovered from boreholes during the field investigation in 1995 (Tables 2). The results indicate the natural water content of the red silty clay was in the range of 17 to 43, with the lower value being due to drying. The average liquid and plastic limits for borehole samples were 36 and 20, respectively. Liquid and plastic limits for samples recovered from exposures and debris in 1993 are higher than values for borehole samples. Samples recovered from the north side of the slide had generally lower natural water content and Atterberg limits than those obtained from the south side. The average liquidity index for all samples was about 0.8. However, a few liquidity index values that were greater than 1 were obtained. A liquidity index of 1 means the soil natural water content is at the liquid limit. When sheared and remolded, soils with a high liquidity index develop low shear strengths.

X-ray diffraction results for an air dried sample (Figure 8) of the red silty clay shows the predominant clay minerals present are illite and chlorite. Peaks for heated and glycol saturated samples are similar to those for air dried samples indicating a relative absence of active clay minerals. This finding is further confirmed by Gleason (1997). The clay fraction ($<2\mu$) from hydrometer analyses is about 62 percent and the activity of the red silty clay is about 0.26. Atterberg limits for the red silty clay plot slightly above and along the A line in a plasticity chart. The clay minerals identified, the activity value and position of the clay in a plasticity chart suggest the red silty clay is inactive. As effective stresses reduce with rising groundwater pressure, the extent of swelling and water content increase for inactive clays would be much less as compared to clays that can be classified as active.

Results of field and laboratory vane shear tests (Table 3) indicate average strengths of 19 kPa peak and 9 kPa residual and average ratio of peak vane strength, Su, to effective overburden stress of 0.22. This ratio is the same as that reported by Larrson (1980) for inorganic clays. The average sensitivity of the red silty clay is about 2. Except for a single value of 5.3, the sensitivity of the red silty clay was below 3.6 for all vane tests. The results suggest that the red silty clay unit in Tully Valley is of low sensitivity. Consolidation results indicated the red silty clay is at near normal consolidation. Although the sensitivity of the red silty clay is relatively compared to sensitive clays, the strength difference between peak and residual is nevertheless not negligible. Where and when peak strength is not mobilized uniformly, the average shear strength over a failure surface would be much less than the peak strength.

A series of isotropically consolidated undrained (CU) triaxial tests were performed on tube samples of the red silty clay. All test samples were of nominal 71 mm diameter with height to diameter ratio of about 2. Each sample was initially consolidated for 24 hours under back pressure to at least twice the present effective stress and maximum past pressure to minimize sample disturbance effects (Ladd and Foott, 1974). At the end of consolidation, the drainage lines were closed to allow arrest of secondary consolidation and pore pressure equalization. The samples were then loaded in compression at a strain rate appropriate for 95 percent pore pressure equalization at failure. The failure envelope for the red silty clay, shown in Figure 9, can be represented by $\phi' = 28.1°$ and $c' = 0$. The average ratio of peak strength to effective consolidation stress for the undrained triaxial compression test results is about 0.30. This

Figure 7: Chloride vs Sulfate (brackish springs)

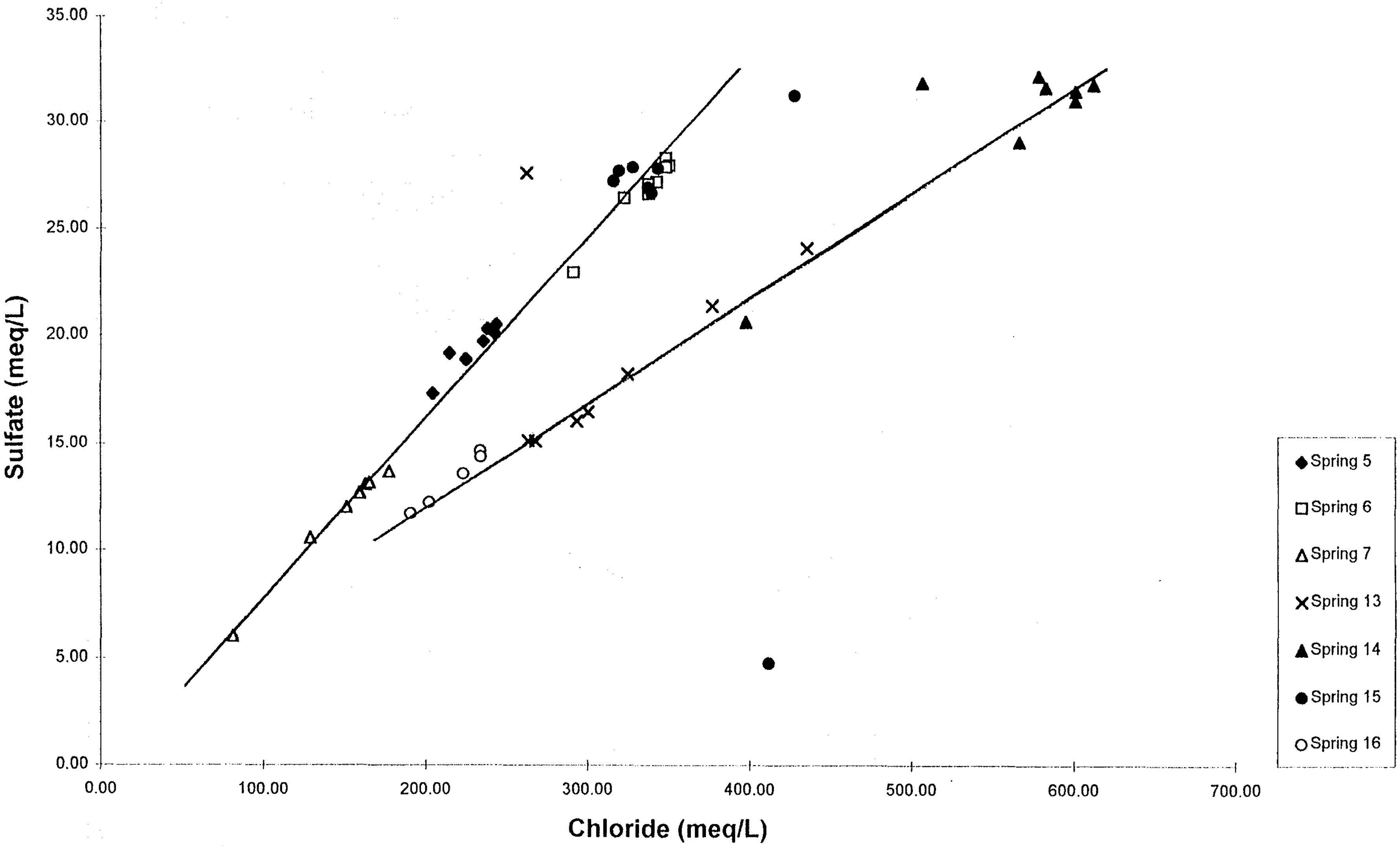


Table 2a- Water content & Atterberg limits (exposures 4/29/93)

SAMPLE	MC (%)	LL (%)	PL (%)	SL (%)	PSS (kPa)	RSS (kPa)	PI (%)	LI	SENSITIVITY
UPPER CLAY									
REMOLDED SAMPLE FROM SLIDE DEBRIS									
4	25.9	52.7	30.6	21.7			22.1	-0.2	
4	27.0	55.0	26.9				28.1	0.0	
UNDISTURBED SAMPLES FROM EXPOSURE AT SLIDE BACK SCARP									
7	34.1	55.2	34.2	24.4			21.0	0.0	
7	32.1	55.4	25.9				29.5	0.2	
8	26.1	51.9	30.6	21.9			21.3	-0.2	
8	29.2	52.8	30.4				22.4	-0.1	
12	17.2	43.6	25.0	18.8	57.5	24.0	18.6	-0.4	2.4
12	29.4	46.5	35.1				11.4	-0.5	
LOWER CLAY									
REMOLDED SAMPLES FROM SLIDE DEBRIS									
1	37.9	32.0	23.4	20.2			8.6	1.7	
1	38.0	34.3	23.3				11.0	1.3	
3	39.6	39.7	28.3	23.4			11.4	1.0	
3	44.0	44.0	27.9				16.1	1.0	
6	36.9	33.2	23.5	20.0			9.7	1.4	
6	38.0	33.3	26.9				6.4	1.7	
EXTRUDED PARTIALLY DRIED SAMPLE FROM SLIDE DEBRIS									
5	24.9	43.5	26.7	20.4			16.8	-0.1	
5	33.0	44.0	28.5				15.5	0.3	
UNDISTURBED SAMPLES FROM EXPOSURE AT SLIDE BACK SCARP									
9	31.9	38.5	23.0	18.0	33.5	12.5	15.5	0.6	2.7
9	35.0	39.0	23.7				15.3	0.7	
11	31.5	32.4	23.4	20.1	30.7	14.4	9.0	0.9	2.1
11	26.0	35.0	21.6				13.4	0.3	
13	38.0	40.5	25.0	19.5	29.7	13.4	15.5	0.8	2.2
13	43.4	41.2	24.6				16.6	1.1	
UNDISTURBED SAMPLE FROM A DISPLACED BLOCK									
10	35.1	36.7	26.6	22.4	24.9	14.4	10.1	0.8	1.7
10	36.0	37.5	17.5				20.0	0.9	

Table 2b - Natural water content & Atterberg limits (borehole samples)

Bore Hole	Depth (m)	Elevation (m)	Sample Type	Soil Type	Atterberg Limits NMC	PL	LL	PI	LI
1a	5.2	164.2	SS	silty c	26.8	16.7	29.0	12.3	0.82
1a	6.1	164.0	ST	silty c	24.0	17.0	28.0	11.0	0.64
1a	12.2	162.1	ST	silty c	36.0	21.0	40.0	19.0	0.79
1a	20.4	159.6	SS	silty c	30.6	19.9	33.0	13.1	0.82
1a	24.4	158.4	ST	silty c	31.0	22.0	35.0	13.0	0.69
1a	26.5	157.7	SS	silty c	29.4	20.9	33.8	12.9	0.66
1a	30.5	156.5	ST	silty c	29.0	18.0	30.0	12.0	0.92
2	6.1	175.8	SS	silty c	40.5	25.7	47.1	21.4	0.69
2	7.0	175.6	ST	silty c	30.0	20.0	32.0	12.0	0.83
2	7.6	175.4	SS	silty c	42.5	25.7	48.3	22.6	0.74
2	9.1	174.9	ST	silty c	37.0	22.0	42.0	20.0	0.75
2	10.4	174.5	SS	silty c	38.2	23.8	41.0	17.2	0.84
2	12.2	174.0	ST	silty c	28.0	18.0	29.0	11.0	0.91
2	13.7	173.5	SS	silty c	29.4	19.4	30.8	11.4	0.88
2	16.8	172.6	SS	varved	30.2	14.5	28.1	13.6	1.15
2	27.4	169.3	SS	varved	18.2	15.1	24.7	9.6	0.32
8a	4.3	170.6	ST	sandy	19.0	22.0	30.0	8.0	-0.38
8a	5.8	170.1	ST	red si	35.0	26.0	45.0	19.0	0.47
8a	7.9	169.5	SS	silty c	39.7	25.0	46.7	21.7	0.68
8a	9.4	169.0	SS	silty c	34.3	22.2	38.9	16.7	0.72
8a	11.0	168.6	ST	silty c	38.0	18.0	39.0	21.0	0.95
8a	12.5	168.1	SS	silty c	28.4	18.5	35.5	17.0	0.58
8a	14.0	167.6	SS	silty c	35.2	19.5	37.9	18.4	0.85
8a	15.5	167.2	SS	silty c	38.3	21.2	34.6	13.4	1.28
8a	17.1	166.7	SS	silty c	17.9	12.0	25.8	13.8	0.43
8b	8.2	172.1	SS	silty c	31.0	21.5	39.7	18.2	0.52
8b	8.5	172.0	ST	silty c	37.0	21.0	37.0	16.0	1.00
9b	9.4	162.0	SS	silty c	33.2	19.2	34.3	15.1	0.93
9b	11.0	161.6	SS	silty c	27.1	17.1	32.0	14.9	0.67
9b	14.0	160.6	SS	silty c	36.9	21.8	34.5	12.7	1.19
9b	15.5	160.2	SS	silty c	30.4	19.5	32.6	13.1	0.83

SS - split spoon ST - shelby tube

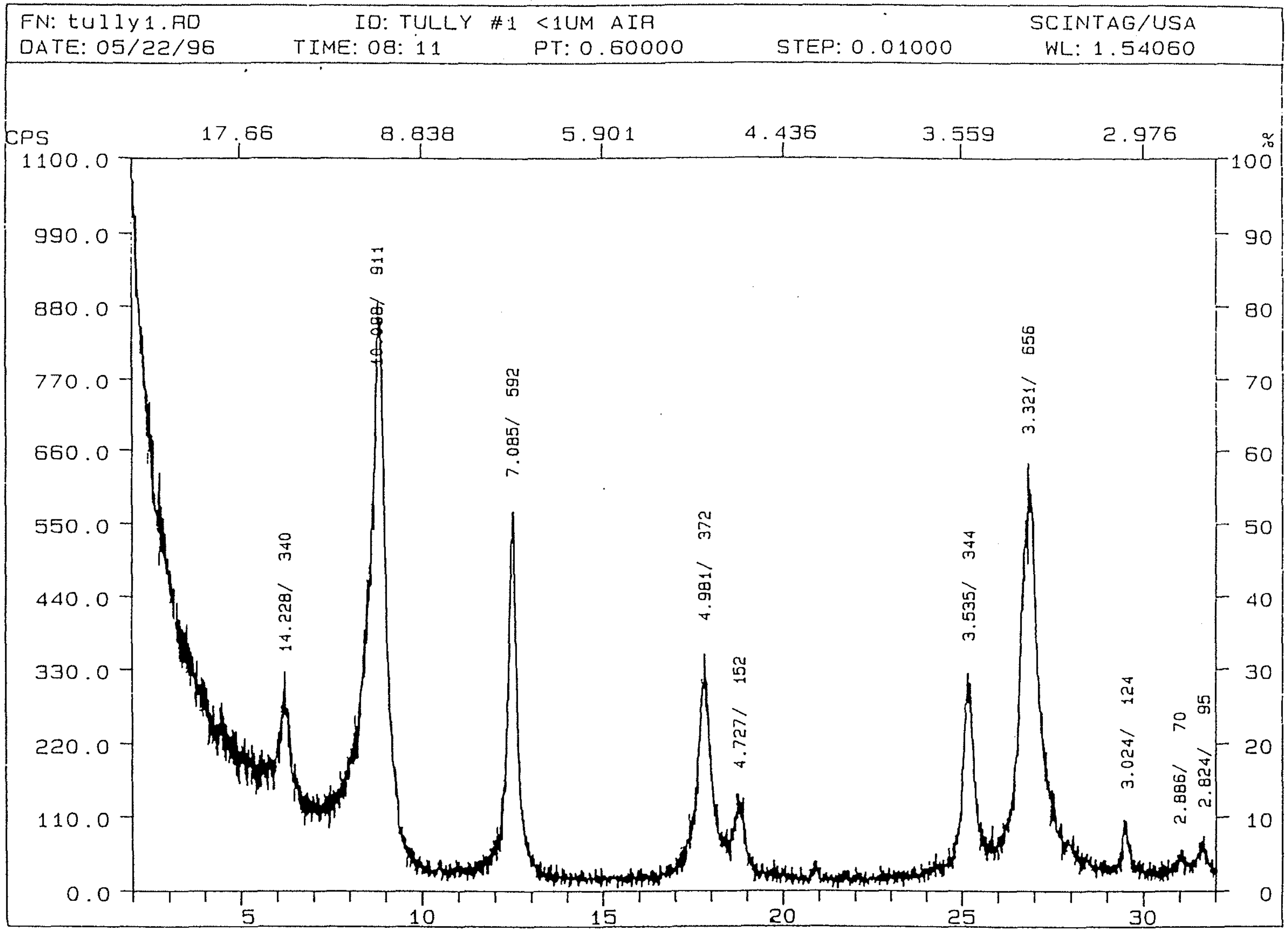


Figure 8 - X-ray diffraction for an air dry red silty clay sample.

TABLE 3 - Vane and CIU shear strengths for the red silty clay

Bore Hole	Depth (m)	Elevation (m)	Test	Soil Type	Su (kPa)	Residual Strength (kPa)	Sensi-tivity	LI	p'(est.) (kPa)	Cu* (kPa)	Su* (kPa)
1a	3.7	164.7	field vane	brown-grey silty clay	37.8	15.7	2.4		54.0	n/a	n/a
1a	6.1	164.0	mini. vane	red silty clay	21.7	11.0	2.0	0.6	59.9	0.9	0.8
1a	7.0	163.7	field vane	red silty clay	11.3	6.3	1.8		67.9	1.0	0.9
1a	12.2	162.1	mini. vane	red silty clay	14.9	4.1	3.6	0.8	52.4	0.7	0.7
1a	12.8	161.9	field vane	red silty clay	15.7	6.3	2.5		55.2	0.8	0.7
1a	18.9	160.1	field vane	red silty clay	22.0	12.6	1.7		102.1	1.5	1.3
1a	24.4	158.4	mini. vane	red silty clay	20.7	6.3	3.3	0.7	95.6	1.4	1.2
1a	25.0	158.2	field vane	red silty clay	26.4	22.0	1.2		94.2	1.3	1.2
1a	30.5	156.5	mini. vane	red silty clay	25.1	8.2	3.1	0.9	87.1	1.2	1.1
1a	31.1	156.3	field vane	red silty clay	28.3	18.9	1.5		89.4	1.3	1.2
2	7.0	175.6	mini. vane	red silty clay	23.4	4.4	5.3	0.8	91.1	1.3	0.8
2	7.6	175.4	field vane	red silty clay	22.0	15.7	1.4	0.7	99.9	1.4	0.9
2	9.1	174.9	mini. vane	red silty clay	8.1	5.0	1.6	0.8	104.2	1.5	0.9
2	9.8	174.7	field vane	red silty clay	18.9	12.6	1.5		100.9	1.4	0.9
2	12.2	174.0	mini. vane	red silty clay	10.7	4.0	2.7	0.9	105.6	1.5	0.9
2	12.8	173.8	field vane	red silty clay	15.7	11.3	1.4		111.0	1.6	1.0
6	9.8	163.1	field vane	red silty clay	12.6	6.3	2.0		85.8	1.2	0.6
6	15.5	161.4	field vane	grey varved clay	18.9	15.1	1.3		67.9	n/a	n/a
8a	4.3	170.6	mini. vane	stiff silt	121.7	28.8	4.2		46.8	n/a	n/a
8a	4.9	170.4	field vane	brown-red silty clay	34.6	6.3	5.5		49.8	n/a	n/a
8a	5.8	170.1	mini. vane	brown-red silty clay	63.6	18.5	3.4		60.1	n/a	n/a
8a	11.0	168.6	mini. vane	red silty clay	15.4	6.1	2.5	1.0	67.1	1.0	0.7
8b	8.5	172.0	mini. vane	red silty clay	36.7	-	-	1.0	57.0	0.8	n/a
8b	9.1	171.9	field vane	red silty clay	15.7	12.6	1.2		67.1	1.0	0.7
8b	12.8	170.7	field vane	red silty clay	15.7	11.3	1.4		70.4	1.0	0.8
9b	16.8	159.8	field vane	red silty clay	15.7	12.6	1.4		92.1	1.3	0.8

Cu* - based on Cu/p'=0.296 +- 0.047 (applies only to red silty clay)

Su/p'=0.220 +-0.074, neglecting vane tests at bh#2@30' and bh#8b@28' (applies only to red silty clay)

Su* - based on average Su/p', neglecting vane tests at bh#2@30' and bh#8b@28' (applies only to red silty clay)

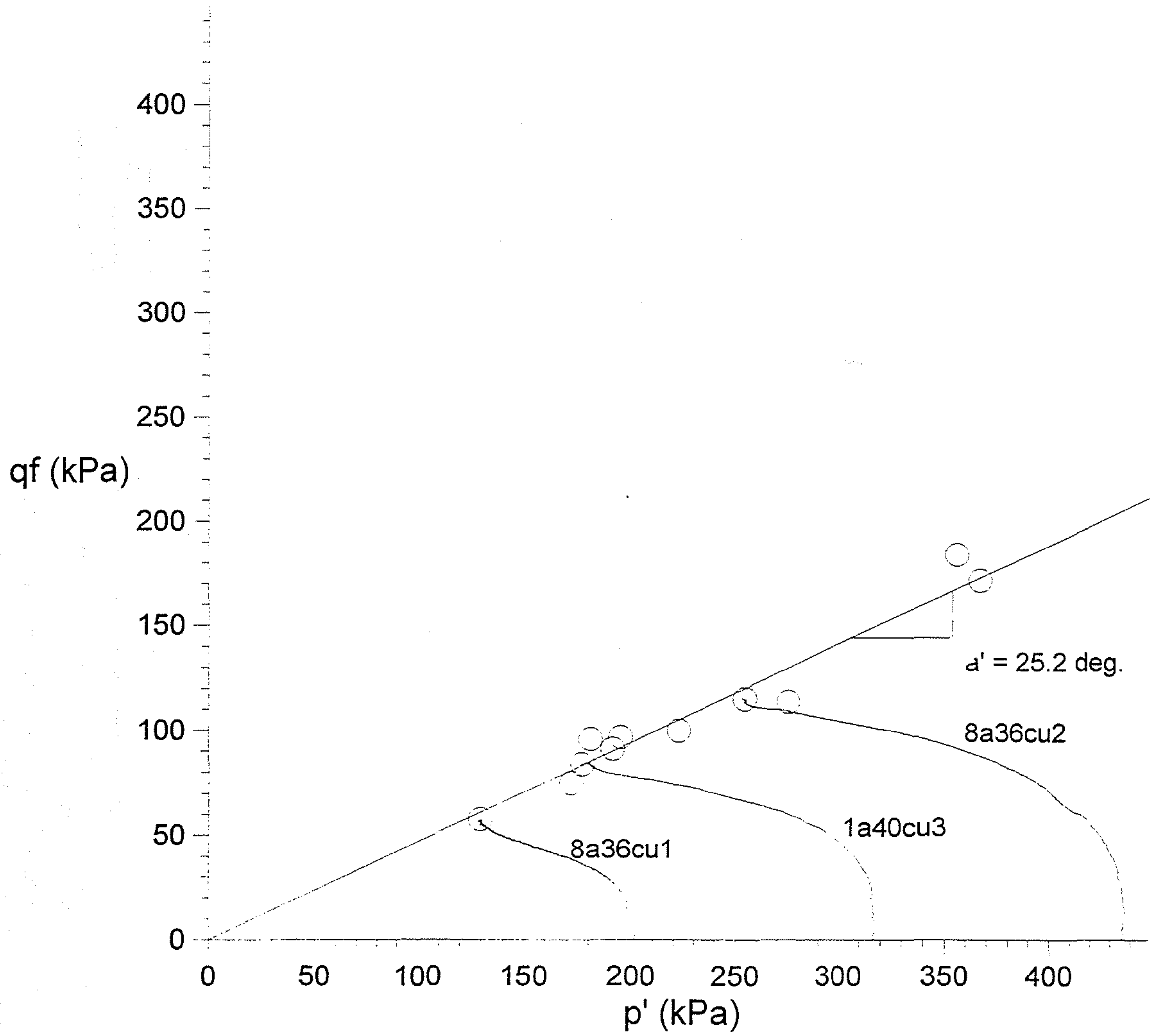


Figure 9 - Typical undrained stress paths and strength envelope for the red silty clay.

ratio is in close agreement with previous results reported for inorganic clays of 0.31 by Larrson (1980) and 0.32 by Ladd (1991). The results reported by Larrson are for isotropically consolidated specimens while those by Ladd are for anisotropically consolidated. Ladd (1991) further reports significantly lower ratios for samples tested in extension and direct simple shear modes. Different modes of failure apply for different segments of a slide surface. Thus the average strength ratio for a failure surface would be less than 0.3.

Stability Analyses

Limit equilibrium stability analyses were performed on three cross sections. Figure 10, represents a fence diagram for the reconstructed stratigraphy through the 1993 slide. Table 4 presents soil properties, other than for the red silty clay, and phreatic surfaces for the analyses. The two other sections analyzed represent existing profiles outside of the slide area along the north and south sides. High groundwater conditions measured in May, 1996 were used. The phreatic surface for the upper sand and varved clay units was later raised to simulate conditions in 1993. The stability analysis program is based on the simplified Bishop method. For a prescribed profile, strength and phreatic conditions, the program identifies the most critical failure surface. Strength parameters for the red silty clay vary depending on the type of stability analysis and depth. Three types of stability analyses; TSA (total stress analysis), ESA (effective stress analysis), and UESA (undrained effective stress analysis) were performed. These approaches to stability analyses are described by Ladd, 1991. Shear strengths used the red silty clay and safety factors obtained by the different types of analyses are given in Table 5.

The TSA analyses considered an undrained failure using shear strength values obtained from field and laboratory vane tests. A condition of $\phi = 0$ was assumed and the undrained shear strength, S_u, estimates correspond to average peak vane strengths. Different average strength values were used for the upper and lower portions of the red silty clay. The boundary separating the red silty clay into two zones is shown in the fence diagram, Figure 10. Factors of safety determined by TSA analyses were low compared to the other types of analyses and well below 1.0 for the failed section. These results are consistent with low safety factor values of 0.60 to 0.85 reported by Bishop and Bjerrum (1960) from TSA analyses for three natural slope failures in normally consolidated clay.

The ESA analyses assumes a drained failure condition using strength parameters of $c'=0$ and $\phi' = 28.1°$. These strength parameters represented the strength envelope determined from the CIU test results. The factor of safety obtained by ESA analyses was 1.35 for the failed section and 2.2 and 2.3 for the north and south sections, respectively. Phreatic surface adjustments to reflect higher estimates for 1993 did not result in values lower than 1 for the failed section. The actual slide event was of short duration and essentially no drainage could have occurred in the red silty clay within the failure time frame. TSA and ESA analyses resulted in too low and too high safety factors, respectively, and were not used in further analyses.

In the UESA analyses, the insitu effective overburden stress, σ', constituted a consolidation stress. Undrained shear strength was prescribed as either $S_u/\sigma' = 0.22$ (based on average vane strengths) or $c_u/\sigma' = 0.3$ (when based on undrained strengths from CIU test results). Failure in UESA analyses was assumed to have occurred under undrained conditions. Safety factors obtained from the UESA analyses were higher than those obtained from the TSA analysis but lower than for ESA. For the failed section, the safety factors obtained from UESA analyses were 1.05 for strengths based on vane shear and 1.31 for strength based on CIU results. The corresponding safety factors for the north and south sections were between 1.31 and 1.98.

All three types of stability analyses were based on ground water levels observed in May 1996. The accumulated precipitation record for Spring 1993 (following a record seasonal snowfall) was higher than the record for 1996. Ground water levels were therefore likely to have been higher at the time of the slide than in May 1996. The phreatic surface for the sand and varved clay interfingers in the back scarp area was raised by a modest 1 m to reflect this condition. UESA analysis with an average undrained shear strength to effective stress ratio of 0.205 resulted in a factor of safety of 0.99 for the failed section. Thus the phreatic surface rise may have been higher and/or the average shear strength to effective stress ratio mobilized over the failure surface was lower.

Table 4 - Soil properties for section F-F

Ref. #	Soil Type	N	Dr* (%)	e*	Density* kN/m3	Sat. Density kN/m3	Su kPa	ϕ deg	Piezometric Surface
1	stiff sandy silt	14	62	0.63	16.2	19.9	-	34	a
2	sand & gravel	-	61	0.4	20.3	21.6	0	36.5	a
3	brown - grey silty clay	-	-	-	-	18.1	57	-	b
4	red silty clay	-	-	-	-	18.5	**	**	b
5	red silty clay	w.r.	-	-	-	18.5	**	**	c
6	grey varved clay	w.h.	-	-	-	18.1	**	-	c
7	till material	50	-	-	-	21.2	81	42	c
8	brown-grey silty clay	56	-	-	-	18.8	167	-	d
9	fine sand	28	78	0.34	19.6	22.1	-	38.8	d
10	weathered shale	76	-	-	22.8	23.1	0	49	d
11	shale	-	-	-	23.6	23.6	240	49	d

* after "Design and Construction of Levees" figure 3-5 (assumes Gs=2.68)
w.h. = weight of hammer w.r. = weight of rod
** see Table 9 (same strength for varved and red clay assumed)

Table 5 - Undrained shear strength and FS

Section	Method	Red silty clay Undrained shear strength	FS
N-N	TSA	ϕ=0, c=Su*=19, 24 kPa	1.09
N-N	ESA	ϕ'=28.1 , c'=0	2.20
N-N	UESA(Su)	Su/p'=0.22, ϕsu=12.4 deg	1.55
N-N	UESA(Cu)	Cu/p'=0.30, ϕcu=16.5 deg	1.98
S-S	TSA	ϕ=0, c=Su*=15,16 kPa	1.15
S-S	ESA	ϕ'=28.1 , c'=0	2.30
S-S	UESA(Su)	Su/p'=0.22, ϕsu=12.4 deg	1.31
S-S	UESA(Cu)	Cu/p'=0.30, ϕcu=16.5 deg	1.56
F-F	TSA	ϕ=0, c=Su*=21,22 kPa	0.86
F-F	ESA	ϕ'=28.1 , c'=0	1.35
F-F	UESA(Su)	Su/p'=0.22, ϕsu=12.4 deg	1.05
F-F	UESA(Cu)	Cu/p'=0.30, ϕcu=16.5 deg	1.31

The deep critical failure surface, shown in Figure 10. is a composite of segments involving different modes of failure. An active mode at the back, direct simple shear at the mid section and extension mode at the front or down slope segment. Failure strengths derived from vane or CIU tests do not represent the full range of failure modes. Peak strengths would also not be mobilized simultaneously over the entire failure surface. Limit equilibrium stability analyses are not convenient for applying different strengths depending on mode of failure and mobilized strain level. Average peak strengths based on CIU compression tests would tend to be over estimates as strengths for direct simple shear and extension modes would be lower. The average strength ratio for the red silty clay suggested by the back analyses was closer to $S_u/\sigma' = 0.22$ obtained from the vane tests.

Remarks

The dramatic Tully Valley Landslide of 1993 occurred in a gentle terrain of about 8° slope. The land area affected by the slide is large and the event was sudden. By common measures of experience there was little to suggest a slide of such magnitude and speed. The stability analyses indicate the portion of slope that had the lowest factor of safety was at the back of the slide basin. Slumping of the upper portions of the slope probably resulted in more loading and subsequent failure through the red silty clay stratum below lower segments of the slope. In the aftermath of the slide, continuous longitudinal cracks normal to the direction of the slide were evident. Fresh and remolded very soft red silty clay was squeezed out through the longitudinal openings. The red silty clay deposit over Tully Farms Road and at the slide front had a high water content and was essentially a mud flow.

The base of the critical failure surface identified by the stability analyses follows a path through the underlying varved clay. Both the varved clay and the overlying sand and gravel interfinger into the red silty clay stratum. These interfingers have much higher hydraulic conductivity and penetrate more than 100 m into the red silty clay. Thus the red silty clay at the interface of the interfingers was exposed to seasonal groundwater fluctuations. Rapid recharge through the interfingers could also have fed more water to the clay, both at the interface and within the varved zone, to enable remolding at above natural water content. The coarse and varved interfinger penetrations into the soft red silty clay and sustained high groundwater levels in March through April of 1993 appear to have been detrimental. The observed difference between peak and residual strength may also have facilitated progressive failure. There is no compelling evidence to date from slope indicator monitoring of significant creep movements along either the north or south sections of undisturbed ground. However, future failure of large sections of undisturbed ground located between the previous slides can not be ruled out without additional investigation.

There is evidence to suggest that secession of the brine mining operation since 1988 has led to a general rise of groundwater levels in lower Tully Valley. How much of this rise has reached the slide site and if such rise constitutes a net increase above pre-mining groundwater levels is not known. The three slides to the north of the 1993 failure are believed to have occurred before the beginning of brine mining in Tully Valley. The recent slide may also have occurred under the record weather conditions experienced in 1993 and without the influence of post brine mining related groundwater rise. What can be said, however, is that a sustained rise in groundwater level would have been unfavorable for stability. The stability analyses confirm the overburden stratigraphy, soil strengths and prevailing piezometric pressures in the back area of the slide were in a condition to initiate a deep seated failure extending through the varved interfinger.

Conclusions

The thick red silty clay stratum is generally soft, inactive and of low sensitivity. A series of sand and varved clay interfingers penetrate into the red silty clay deposit. Piezometric pressures fluctuate seasonally within the interfingers but not significantly in the red silty clay stratum. The 1992-93 Winter produced a record snowfall in Tully Valley. Unusually high groundwater conditions appear to have been sustained throughout March and April of 1993. Portions of the red silty clay at the interface with the sand and varved clay interfingers became exposed to the high groundwater pressures. More water became readily available to permit remolding at a high water content in the failure zone at the interfinger interfaces. The observed difference between peak and residual strengths is significant. The failure probably developed slowly and progressively until the final stage of rapid sliding. These conditions

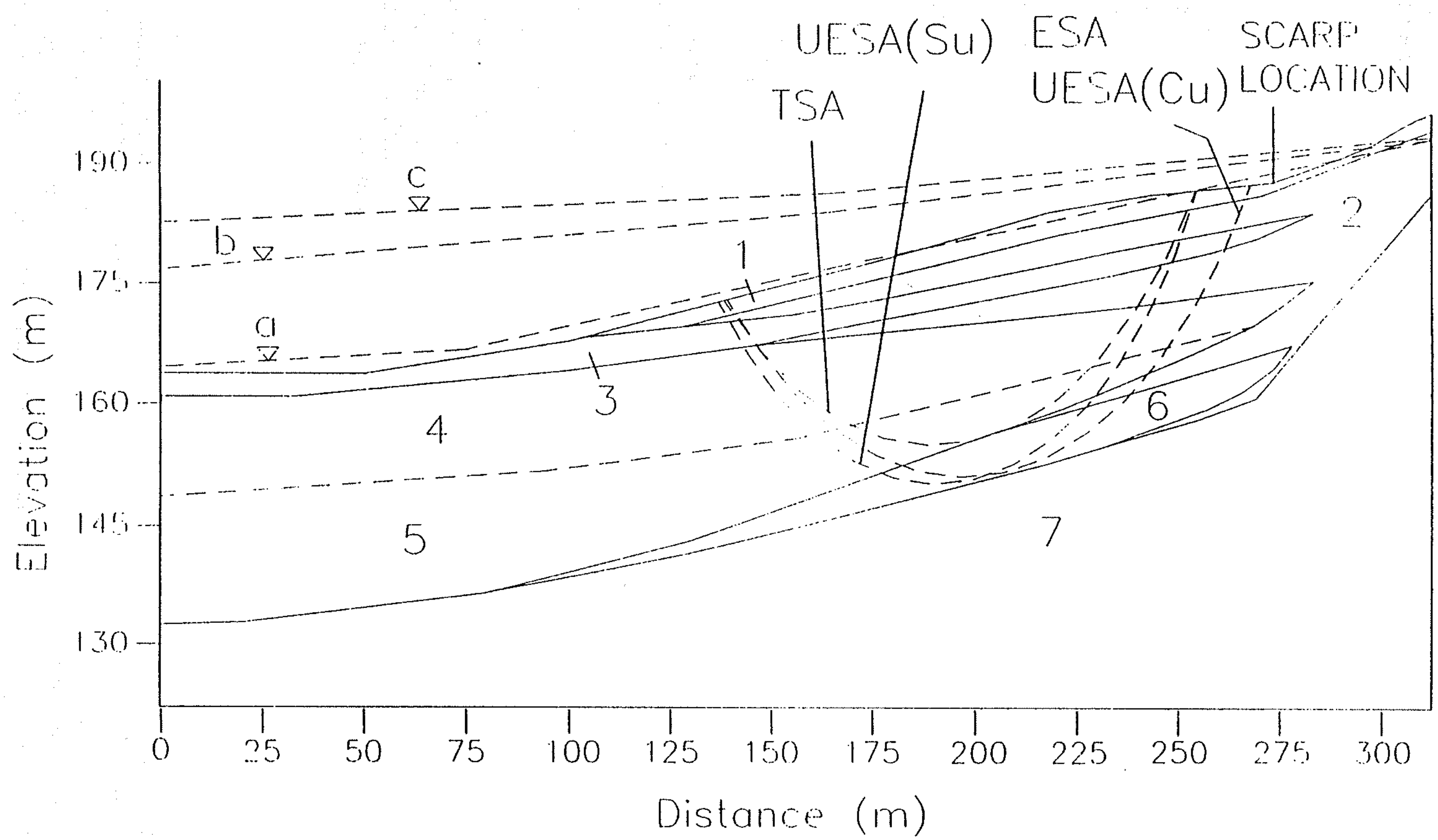


Figure 10 - Fence diagram for stability analyses and critical failure circles.

appear to have combined to cause the landslide. Prospects for future slide hazard at other locations to the north of the 1993 slide need to be observed and examined.

Acknowledgment

Financial support for this investigation provided by the National Science Foundation is gratefully acknowledged.

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Hydrology, Geology, and Remediation of Tully Valley Mudboils, Onondaga County, New York

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Introduction

The history of mudboil activity in the Tully Valley (fig. 1) can be traced back nearly 100 years. A detailed description of one mudboil is given in an article in the Syracuse, N.Y. Post Standard, dated October 20, 1899:

> "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 to and 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 over Onondaga Creek (fig. 2) 92 years later, in 1991.

In the early 1900's the U.S. Geological Survey (USGS) performed a "postmaster" survey of the water resources of Onondaga County, in which local postmasters were asked to respond to a one-page questionnaire concerning springs, artesian wells, and other ground-water features. The only reference in the survey to possible mudboil activity was found on an undated map, annotated by USGS personnel, indicating a location for "sand springs" near the Otisco Road bridge. Other reports of mudboil activity in the valley have been gathered from anecdotal conversations with local residents and from various State and local governments by the New York State Department of Environmental Conservation (Snell, 1992). The bulk of the reports began after 1950 but were preceded by sparse recollections from local residents, although a a 90-year old individual in 1993 reported a vivid recollection of her brother falling into, and being rescued from a mudboil in the early 1900's.

In 1951 the New York State Health Department (Snell, 1992) reported high turbidity and stated that suspended sediment "enters the stream south of Cardiff, N.Y. from springs and potholes." Reports from the Onondaga Nation (about 2 miles north of the Tully Valley) indicated that Onondaga Creek became turbid year-round in the early 1950's. Another New York State Health Department report in 1955 indicated that the turbidity in the creek came from "quicksand pits" near Onondaga Creek tributary T-21, south of Otisco Road (Snell, 1992). A full summary of these reports is given in Kappel and others (1996).

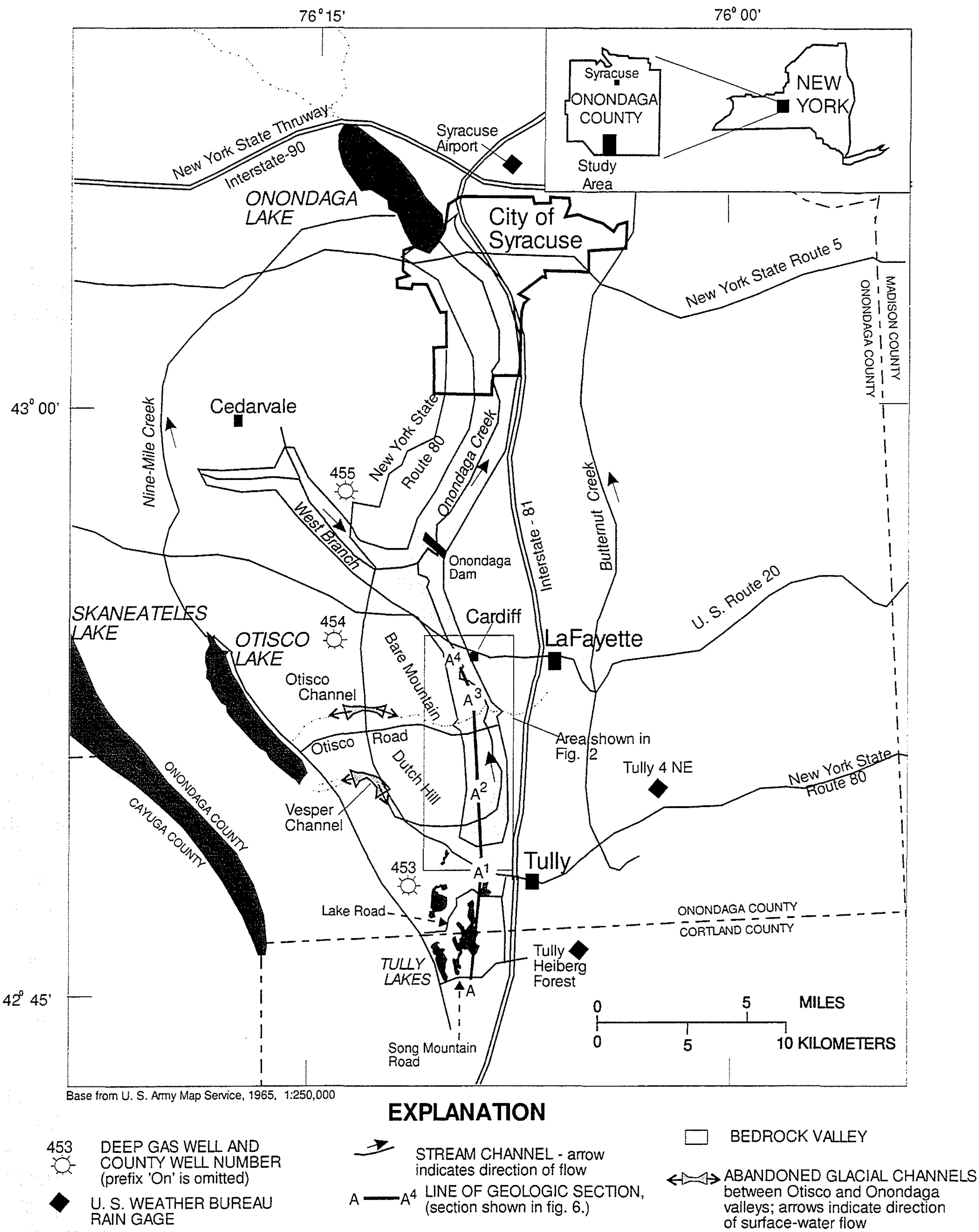


Figure 1. Location and pertinent geographic features of the Tully Valley, and location of geologic section A - A^4 in southern Onondaga County, N.Y. (Geologic section shown in fig. 6. From Kappel and others, 1996, fig. 1.)

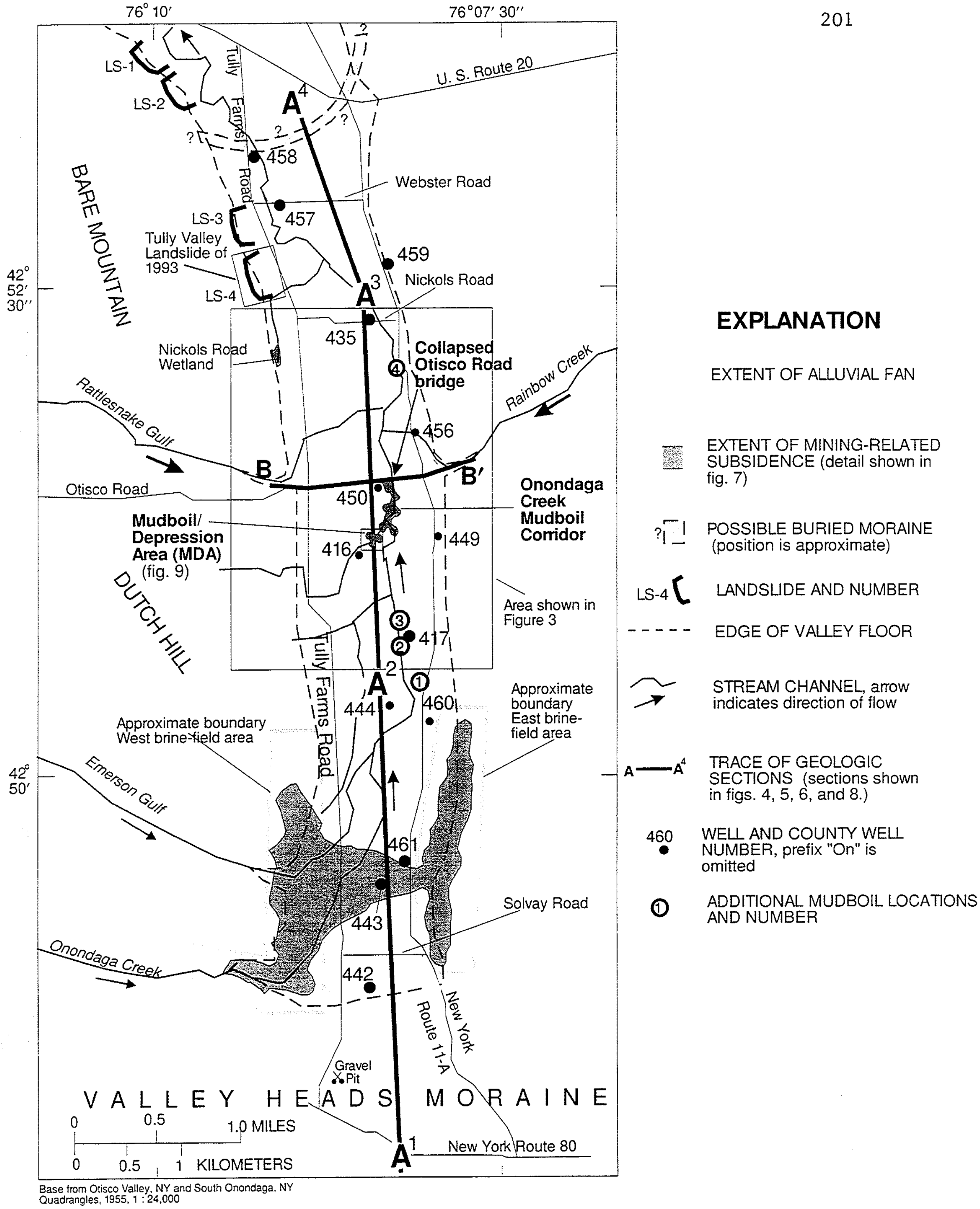


Figure 2. Principal geographic features of the Tully Valley showing wells, brinefield areas, landslides, mudboils, and geologic sections A-A⁴ and B-B′ (Geologic sections shown in figs. 4, 5, 6, and 8. From Kappel and others, 1996, fig. 2)

Waller (1977) reported that water discharging from the main mudboil/depression area (MDA) in the mid-1970's was fresh, but his later fieldnotes indicate that, by 1979, some mudboils were discharging brackish water (R.M.Waller, USGS, written commun., 1993). These fieldnotes are the only source of water-quality information on the mudboils from the 1970's through the 1980's.

In 1991, the USGS, in cooperation with the Onondaga Lake Management Conference (OLMC) and the U.S. Environmental Protection Agency (USEPA), began a 4-year study to identify the extent and mechanism of mudboil development in the Tully Valley. An extensive test-well-drilling program was implemented to document the glacial stratigraphy and aquifer conditions near the mudboil area, and a deep test well was installed that penetrated the salt beds from 950 feet to about 1,100 feet below land surface. Streamflow entering and leaving the MDA, and chemical and physical quality of water upstream and downstream of the MDA, were monitored to characterize mudboil water quality and quantity within the MDA. Results are summarized below:

Mudboil Flow System

Some mudboils are found within a 300-foot-wide by 1,500-foot-long corridor along Onondaga Creek, just upstream from the two side-valley alluvial fans, and within a 5-acre subsided area (the MDA) along a tributary of Onondaga Creek, near the south end of the mudboil corridor (fig. 3). Mudboil discharge is driven by artesian pressure in two unconsolidated aquifers. The upper (freshwater) aquifer is confined by a 60-foot layer of reddish-gray silt and red clay; the lower (brackish-water) aquifer is confined by a layer of red, dense, clay till about 10 feet thick (fig. 4). Artesian pressure in these aquifers causes hydrostatic heads to be 20 to 30 feet above land surface over most of the valley floor and exceeding 30 feet along Onondaga Creek in the vicinity of the Rattlesnake and Rainbow Creek alluvial fans. The source of the artesian pressure that drives mudboil activity is recharge from the Valley Heads Moraine at the southern end of the valley, the alluvial fans of Rattlesnake Gulf and Rainbow Creek, and minor recharge from the valley walls.

Sediment Concentrations and Loading to Onondaga Creek

Suspended-sediment concentrations at the outlet of the MDA ranged from 31,200 mg/L (milligrams per liter) in October 1991 to 17 mg/L after some remediation efforts were implemented in the summer of 1993. Yearly average suspended-sediment loads to Onondaga Creek from the MDA for water years 1992-96 were 29.8, 9.75, 1.41, 1.80, and 2.80 tons per day, respectively. Sediment discharged from the MDA was initially 30 to 60 percent clay and 80 to 100 percent silt-sized or smaller particles; the sand-size fraction never exceeded 20 percent. After remediation projects were implemented, 50 to 80 percent of the discharged sediment was clay, and nearly all sediment was silt-sized or smaller. The medium sand fractions immediately settle out as a mudboil "cone" and remain within the depression area.

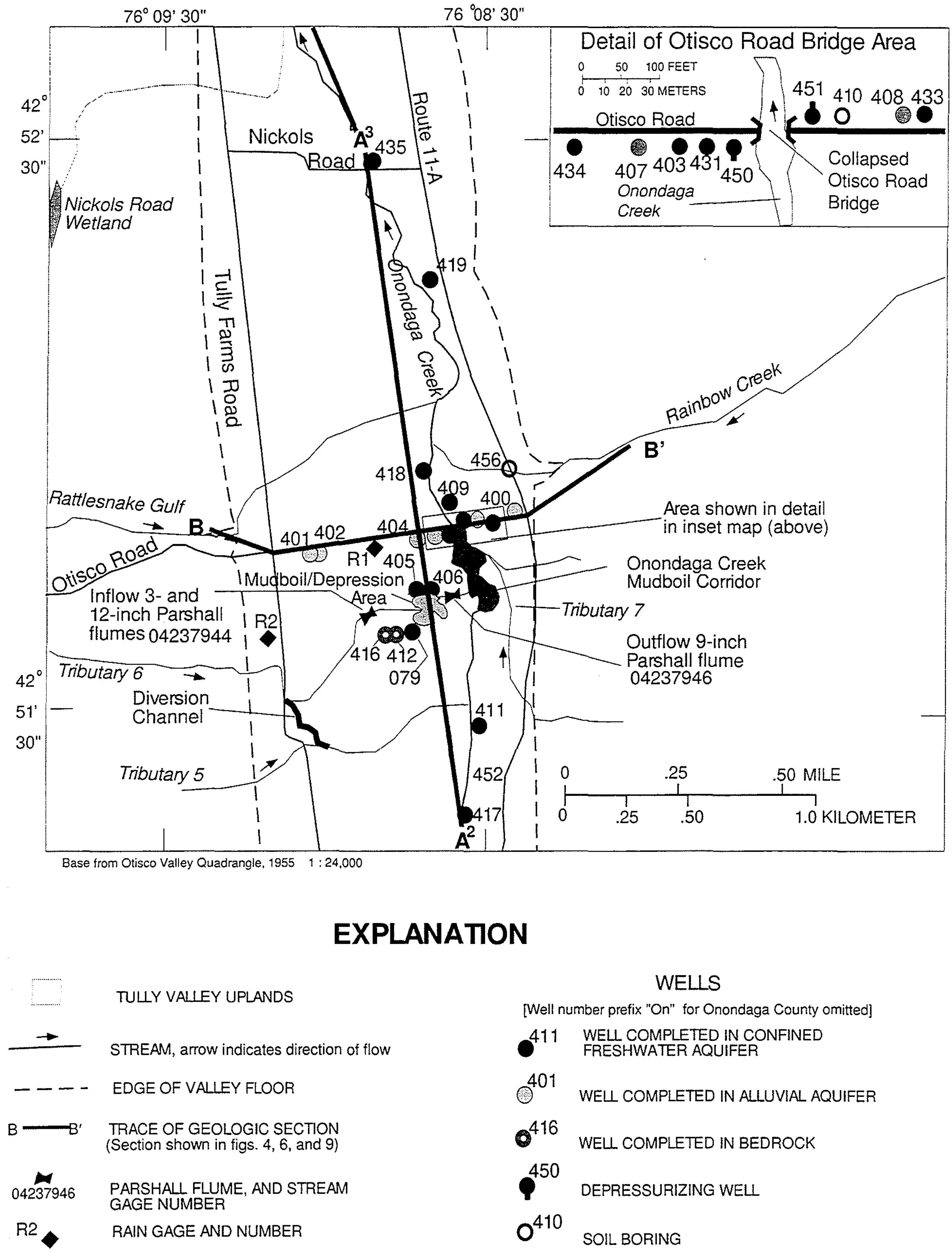
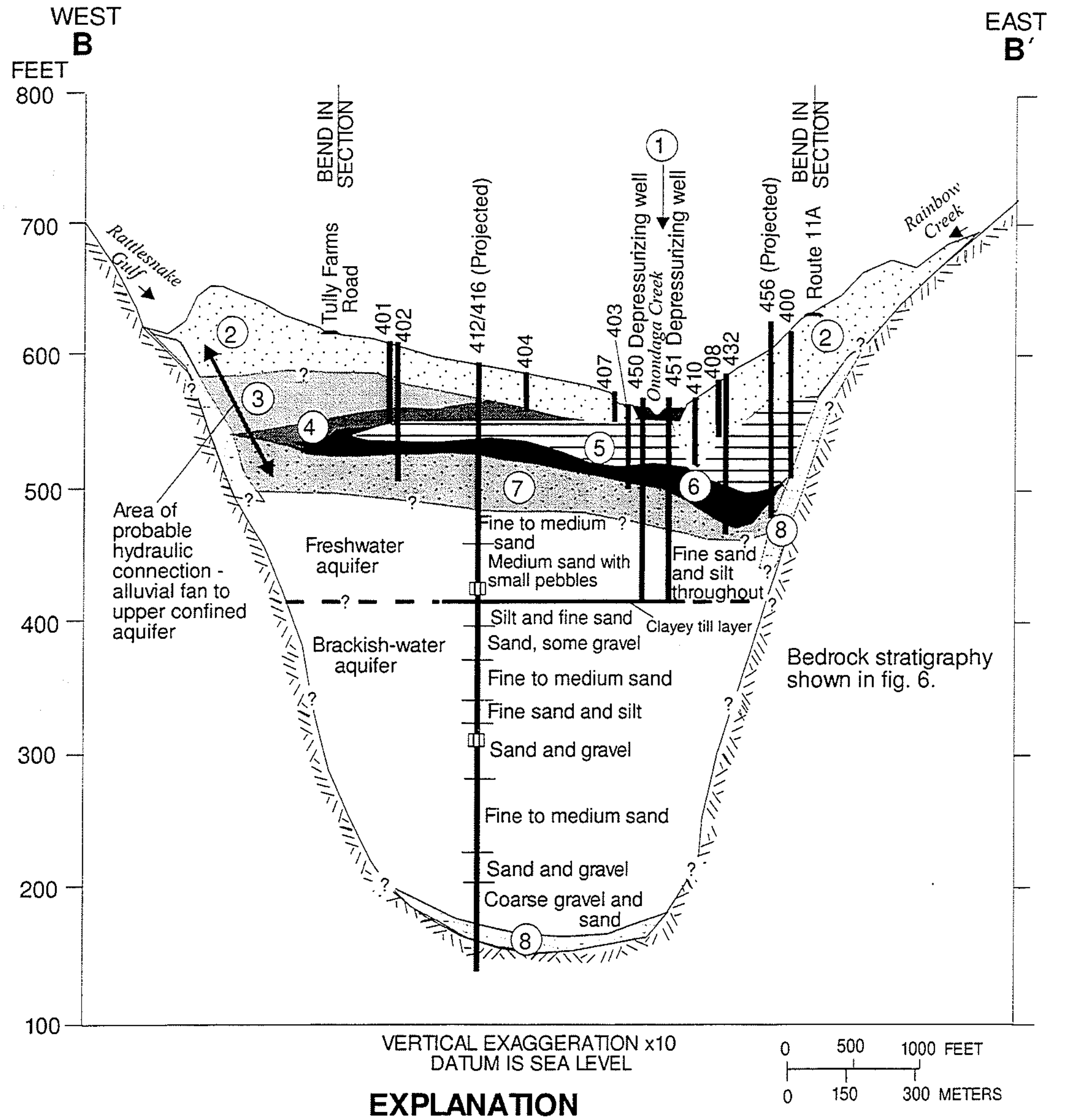


Figure 3. Location of wells, Parshall flumes, raingages, and geologic sections A^2- A^3 and B-B′. (Location is shown in fig. 2. Geologic sections shown in figs. 4, 6, and 8. From Kappel and others, 1996, fig. 5.)



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 farther 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 farthest in the proglacial lake. Coarser sand is found along Otisco Road; finer sand-to-silt wisps are found farther north and south of Otisco Road. Forms the top of confining unit over the liquifiable sand and silt unit in the mudboil areas.

LACUSTRINE DEPOSITS (cont'd)

(6) CLAY AND SILT - Massive unit that generally covers most of the 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 the bottom. 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 "On" prefix

MONITORING ZONE, steel casing perforated after hydraulic testing of deeper bedrock zones and grouting of the bedrock section of deep well On-416.

Figure 4. Geologic section B-B′ showing upper unconsolidated deposits along Otisco Road and deeper unconsolidated deposits projected from well On-412, southwest of the mudboil/depression area. (Location of section shown in figs. 2 and 3.)

Chemical Quality of Water from Confined Aquifers

Specific conductance of water from the confined upper (freshwater) aquifer ranges 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 confined lower (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. Trend analysis indicates that the specific conductance of water leaving the MDA has increased by about 200 µS/cm per year since 1992, and the chloride content in the upper (freshwater) aquifer appears to be increasing.

Bedrock Geology

Stratigraphy

The Tully Valley lies within and above bedrock units of Middle Devonian through upper Silurian ages. The bedrock ridges, 1,000 to 1,200 feet above the Tully Valley floor, are shale, limestone, and siltstone of Middle Devonian age (Rickard, 1975). The Tully Limestone is found near the top of Bare Mountain, and the valley wall consists of the Hamilton Group Shales to a depth of 300 feet below the valley floor (fig. 5). The Hamilton Group is underlain by the Onondaga Limestone Formation, the Oriskany Sandstone, and the Helderberg Group of limestones and dolomites. The Onondaga Limestone acted as an erosion-resistant ramp for glaciers in most of the other Finger Lake valleys (Mullins et. al., 1991), but the deep drillhole at the MDA (fig. 5) indicates that glacial action in the Tully Valley eroded down to the middle of the Helderberg Group, within the Manlius or Rondout formations (Brayton Foster, private consultant, written commun., 1993).

Below the Helderberg Group lies the Upper Silurian Salina Group and the Syracuse Formation which contains the evaporite deposits that were solution mined in the southern part of the valley (fig. 6). Gas-well logs west of the Tully Valley, and logs from the brine-field wells, indicate that the evaporite beds are about 150 feet thick and gradually thin and pinch out as they rise to the north. The northern end of the Tully Valley apparently is near the edge of the Salina salt basin, as indicated by Rickard (1975).

Strike and Dip

Bedrock strike and dip sets above and below the Syracuse Formation were computed from brine-field and gas wells logs in and near the Tully Valley. Four strike and dip sets are present: (1) in the valley, above the Syracuse Formation, the strike is N. 48° E., with a dip of 71 feet per mile to the southeast; (2) west of the valley, logs of gas wells indicate a strike of N. 75° W., and a dip of 83 feet per mile to the southwest; (3) data below the Syracuse Formation are limited, but the in-valley strike for the top of the F2 saltbed (fig. 5) is N. 27° E., with a dip of 89 feet per mile to the southeast; (4) the strike of the top of the Vernon Shale is N. 48° W., with a dip of 58 feet per mile to the southwest. The differences in strike and dip among these beds could be related to

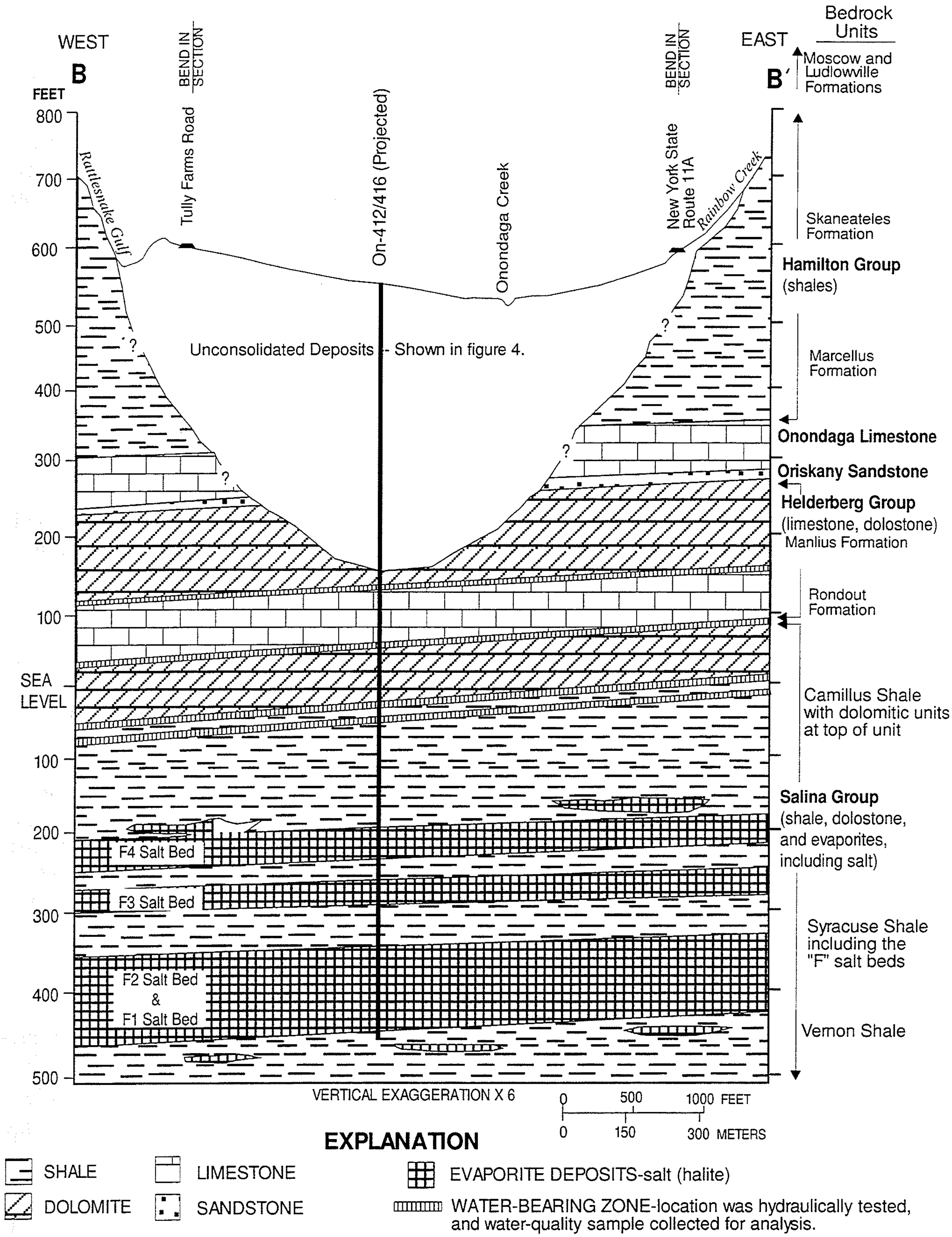


Figure 5. Geologic section B-B′ showing major bedrock units below Rattlesnake Gulf and Rainbow Creek from lower valley walls to top of Vernon Shale. (Modified from Getchell,1982, plate 1. Location of section shown in figs. 2 and 3.)

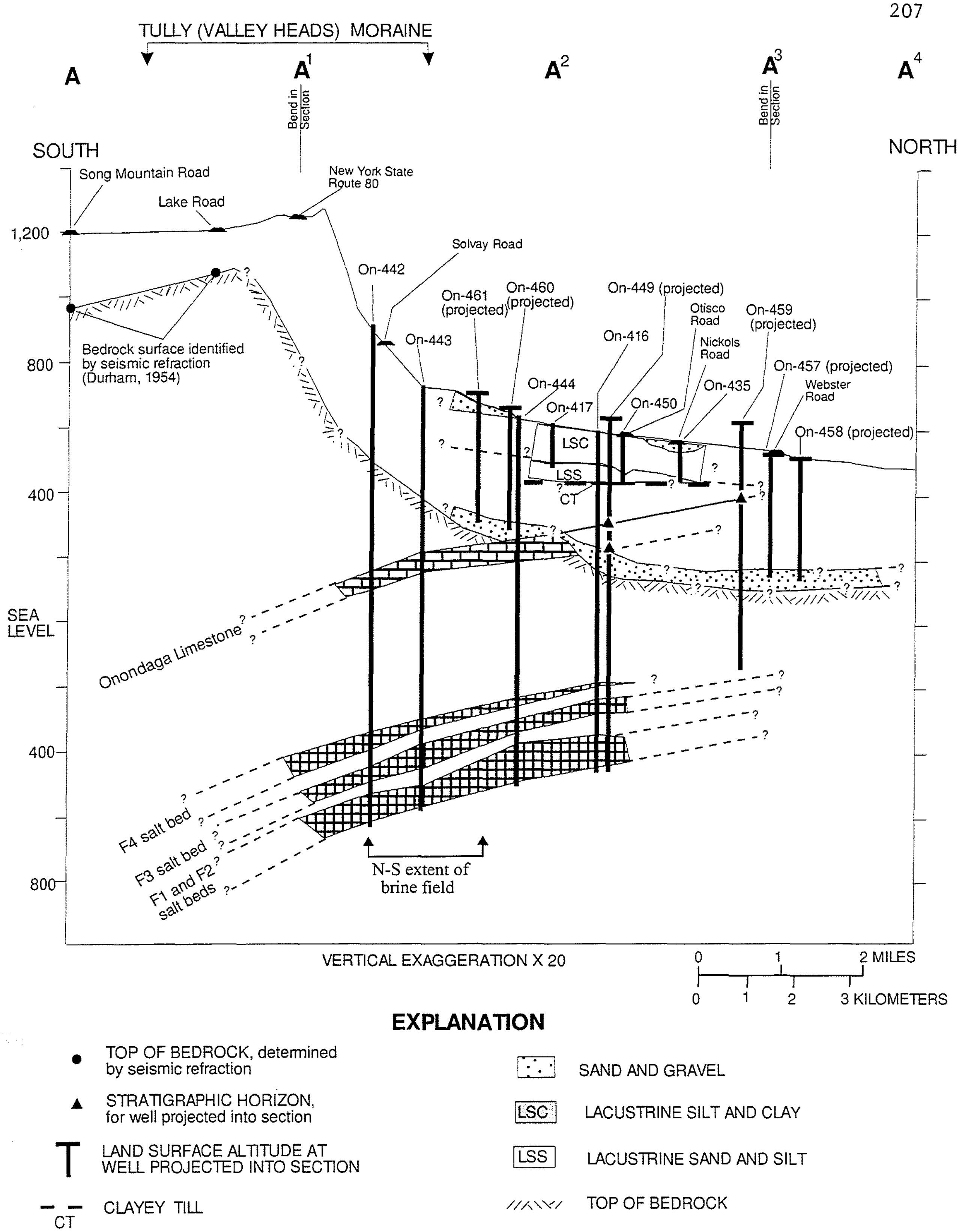


Figure 6. Geologic section A-A^4 from the Tully Lakes through middle part of the Tully Valley showing position of the Salina "F" salt beds, Onondaga Limestone, bedrock floor and generalized unconsolidated units in the mudboil area near Otisco Road (Location shown in figs. 1 and 2. From Kappel and others, 1996, fig. 5.)

localized folding above and below the décollemont surface within the saltbeds, localized upwarping (Matheson and Thomson, 1973; and Molinda and others, 1992) from the removal of 1,200 ft of bedrock by glaciation, and(or) recent rebound from glacial unloading.

Vertical fracture patterns as determined by Getchell (1983) and DeGroff (1950) are roughly north-south with a nearly orthogonal east-west set. These coincide with those on a map of photo-linear features in this area by Isachsen and McKendree (1977). Haley and Aldrich of New York (1991) describe a fault surface within the brine field striking N. 74° W. and another possible structure striking roughly north-south, in or near the east brine-field area. These north-south structures may coincide with several north-trending bedrock features on the east-facing, upper slope of Bare Mountain that strike N. 7° W. and extend hundreds of feet in the Tully Limestone and in several sections of the upper Hamilton Shales. In the brinefield area, these strike and dip features and other bedrock fractures may have been enhanced or distorted by 100 years of salt-solution mining (fig. 7).

Glacial Geology

Tully Valley Sequence

Two sequences of upward-fining deposits were indicated by analysis of split-spoon samples taken every 10 feet from the deep drillhole (On-416) near the MDA (fig. 4). The lowermost unconsolidated unit consists of a dense bed of clayey sand, gravel, and boulders (till) overlain by beds of coarse sandy and bouldery gravel with interbeds of silt. A finer grained unit above grades from coarse sand to silt and clay. A readvance of the ice front compacted the fine-grained unit and, as the glacier again receded to the north, it laid down another coarse to fine-grained sequence that was capped by the 60-foot thick silt and clay layer that forms the present valley floor.

Rattlesnake Gulf - Rainbow Creek Sequence

As the ice front was discharging fine materials into the glacial lake (Grasso, 1970), coarse to fine-grained materials were being discharged into the main valley from the two major side valleys (Rattlesnake Gulf and Rainbow Creek), and fine-grained particles (sand, silt, and clay) were settling in the central part of the lake. Stratigraphic logs from wells drilled along Otisco Road and Onondaga Creek indicate a bowl-shaped deposit of laminated clayey silt with interbeds of fine to medium sand. The deepest part of the laminated sequence appears to be at the intersection of Otisco Road with Onondaga Creek (fig. 8). This laminated sequence was laid down contemporaneously with the Tully Valley upper fine-grained valley-floor deposit.

Remediation Activities

Three remediation projects, described below, were implemented by the Onondaga Lake Management Conference on the basis of the above-mentioned research to reduce sediment discharge to Onondaga Creek and to slow or stop mudboil activity.

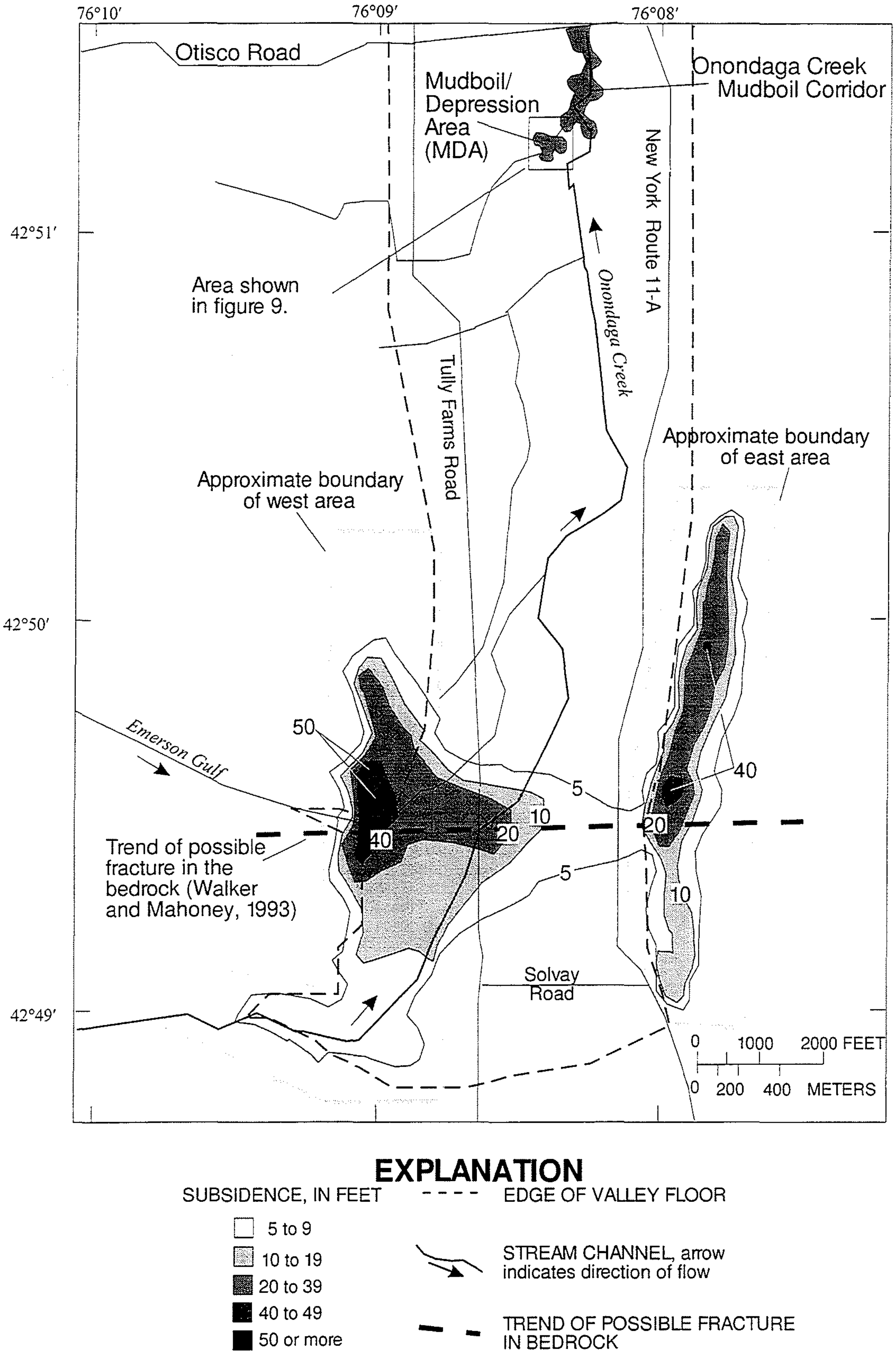


Figure 7. Extent and depth of brine-field subsidence (1957-93) in east and west areas and along a possible bedrock fracture in the southern part of Tully Valley (Modified from Walker and Mahoney, 1993, figure 7. Location shown in fig. 2.)

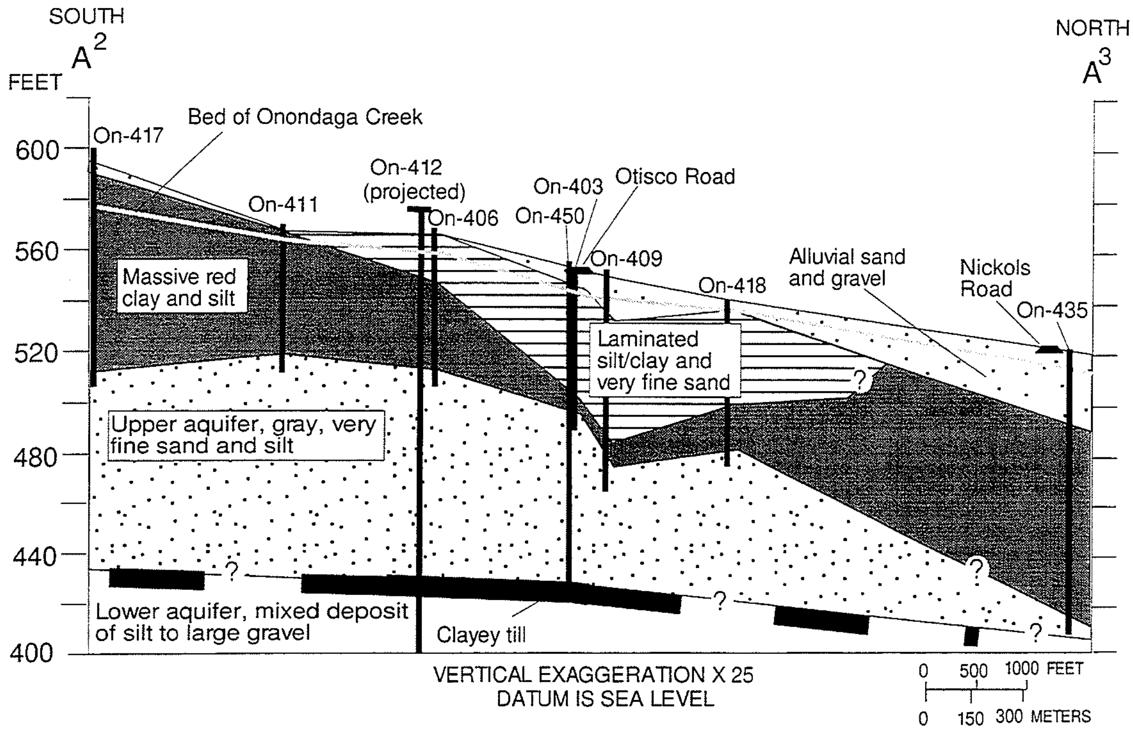


Figure 8. Geologic section A²-A³ showing unconsolidated deposits in the central part of the Tully Valley and the projected thickness of the confined freshwater aquifer between wells On-417 and On-435. (Location of section shown in figs. 2 and 3. From Kappel and others, 1996, fig. 5.)

Stream Diversion

Flow from the 0.7 square mile watershed above the MDA was diverted away from the MDA area to another tributary just to the south in June, 1992 (fig. 3). This diversion reduced the amount of water entering the MDA by about one-third and reduced the amount of sediment discharging to Onondaga Creek by about 30 percent of the load measured before the diversion.

MDA Impoundment

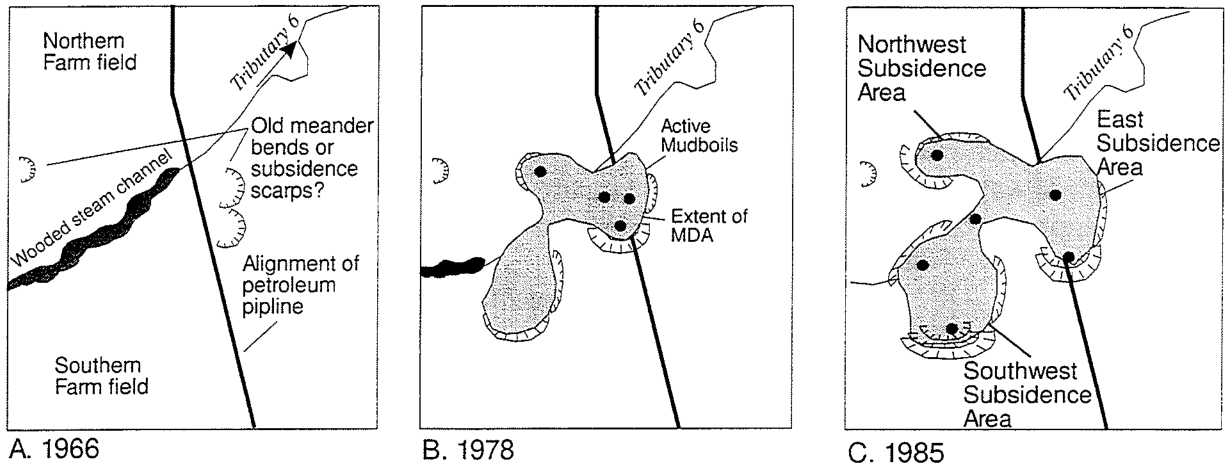
A temporary dam was constructed at the outlet of the MDA to: (1) impound flow and thereby retain sediment discharged from the mudboils, and (2) to increase the hydrostatic and lithostatic loads over mudboils within the MDA and thereby reduce discharges of water and sediment from the mudboils. The dam caused water to inundate mudboils in the eastern and central part of the MDA and was initially successful in reducing the sediment discharge to Onondaga Creek to less than 0.5 tons per day. The impounded area soon filled with sediment, however, and the loading of clay and fine silt particles to the Creek increased. A new, permanent dam that can impound up to 5 feet of water behind it was constructed in October 1996 at the outlet of the MDA. Water levels will be raised incrementally, as the pond fills with sediment, in conjunction with operation of depressurizing wells around the MDA.

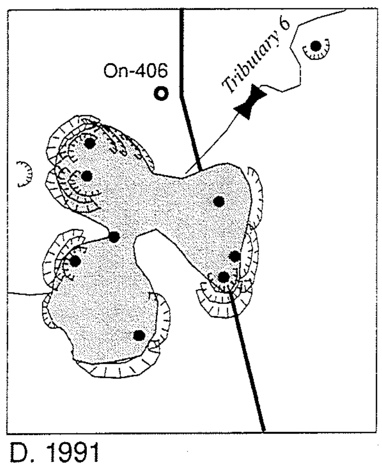
Depressurizing Wells

Two depressurizing wells were installed near the Otisco Road bridge in December 1993 to lower the artesian pressure and thereby reduce mudboil activity near the bridge. A properly constructed well will keep mudboil sediments in place while discharging ground water faster than a mudboil. Each well consists of a 12-inch surface casing driven into the upper 40 feet of the upper silt and clay unit, with an interior 6-inch casing driven through the silt and clay unit into the upper freshwater aquifer. The interior casing was driven to the top of the clayey till unit, about 130 feet below land surface, and then cleaned out. The types of sediment removed from the casing were logged to identify the most permeable unit between the clayey till and the surficial silt and clay sediments. A screen was lowered to a position opposite the most permeable unit, and the casing was pulled up to expose the screen. The permeable unit outside the screen was then developed to produce a flow of sediment-free water.

Flow from the well on the west side of the bridge averaged about 23 gal/min (gallons per minute), and the well on the east side averaged about 3 gal/min. The coarsest unit observed in the well on the east side of the bridge was a fine sand; the west-side well had a medium sand. The wells reduced the artesian pressure within a radius of at least 200 feet by about 2.5 feet, as determined by monitoring wells installed previously. Mudboil activity, which caused the collapse of the bridge in 1992, has not resumed. The wells were not necessarily the sole reason for the decline in mudboil activity because the onset and cessation of flow from any given mudboil are poorly understood.

The success of the two depressurizing wells at the Otisco Road bridge prompted the installation of eight additional wells along Onondaga Creek and around the MDA in the fall of 1996, in conjunction with the reconstruction of the MDA-outlet dam. These wells were needed to reduce any increase in artesian pressure resulting from the additional water and sediment load over the





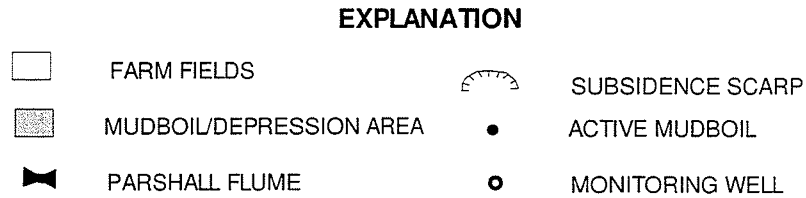


Figure 9. Development of the mudboil/depression area as interpreted from aerial photographs of 1966, 1978, 1985, and 1991. Diagrams are representative of scarp development but are not to scale because the photographs were taken from differing heights and angles. Location shown in fig. 2. (Photos from U.S. Department of Agriculture - Agricultural Stabilization and Conservation Service 1966, 1978, and 1985; Onondaga County Department of Planning 1991. Fig. 3 from Kappel and others, 1996, fig 14.)

mudboils within the MDA. The discharge from these wells ranged from more than 130 gal/min to less than 5 gal/min. Water from the MDA and Onondaga Creek wells range from fresh (<500 μS/cm) to very brackish (>19,000 μS/cm). Brackish water was encountered in some wells in which the clayey till layer was not found during drilling. In other wells, only fine-grained materials were found, and well yields were correspondingly low.

Coarse gravel was penetrated in one well on the northwest side of the MDA at a depth of about 170 feet. Flow from the well exceeded 300 gal/min initially but soon slowed to less than 50 gal/min as sand and gravel were forced up into the casing. Water from this well was extremely brackish; therefore, the decision was made to seal this well and drill another nearby. Within minutes, however, small mudboils appeared about 25 feet from the site, and the water discharged from these mudboils was also extremely brackish. This area was suspected to have been the edge of a old mudboil area (fig. 9D), and the sudden, rapid development of the mudboils discharging brackish water confirmed this. A grouting company was hired to seal the base of the well and the hydraulic connection to the surface, but this procedure failed. Within days, a large, consolidated mudboil vent developed that discharged about 100 gal/min of extremely brackish water and sediment to the upper end of the MDA. Soon thereafter the land began to subside, but within 3 months, the subsidence slowed, as did the rate of flow from the mudboil. At present (August 1997) the area is fairly stable but will probably coalesce with the MDA eventually.

Future Considerations

The mudboil area is dynamic and difficult to remediate. The wells around the MDA at present discharge about 350 gal/min, which drains to Onondaga Creek. Water leaving the MDA impoundment is almost clear and lacks coarse-grained silt and sand. The results of these remediation activities will be evaluated over the next several years to determine their effectiveness in reducing the artesian pressure, slowing mudboil activity and land subsidence, and reducing the loading of sediment to the creek. Increasing chloride concentrations discharged to the creek from the mudboils (and mudslide areas) will also need to be monitored to assess the effect of remediation on Onondaga Creek.

Acknowledgments

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