Prepared in cooperation with Onondaga Lake Partnership and Onondaga Environmental Institute

Causes and Movement of Landslides at Rainbow Creek and Rattlesnake Gulf in the Tully Valley, Onondaga County, New York

Scientific Investigations Report 2009–5114

U.S. Department of the Interior
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Cover. Left side picture—Upper scarp of the Rainbow Creek landslide - Spring 2007
Right Side picture—Toe of Rattlesnake Gulf slide which has blocked Rattlesnake Gulf Creek - Summer 2006
Background picture—Rainbow Creek slide in early spring

Causes and Movement of Landslides at Rainbow Creek and Rattlesnake Gulf in the Tully Valley, Onondaga County, New York

By Kathryn L.Tamulonis, William M. Kappel, and Stephen B.Shaw

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Conversion Factors and Datum

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per minute (ft/min)	0.3048	meter per minute (m/min)
foot per hour (ft/hr)	0.3048	meter per hour (m/hr)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
inch per hour (in/h)	0.0254	meter per hour (m/h)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C)+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F-32)/1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

List of Acronyms

Cal BP years	Calibrated years before present
^{14}C yr B.P.	Carbon-14 years before present
USGS	U.S. Geological Survey

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Causes and Movement of Landslides at Rainbow Creek and Rattlesnake Gulf in the Tully Valley, Onondaga County, New York

Kathryn L. Tamulonis[1], William M. Kappel[2], and Stephen B. Shaw[1]

Abstract

Two landslides in the Tully Valley of central New York are moving slowly toward their respective streams (Rainbow Creek and Rattlesnake Gulf). Data on soil displacement (landslide movement), groundwater levels in both landslide areas, and precipitation on the Tully Valley floor were collected from June 2006 through June 2008. Analyses of the data indicate the displacement of shallow, weathered soils in upslope areas is related to heavy rainstorms and the associated rise in groundwater levels above the unweathered soil layer, whereas shallow-soil displacement on the lower, steepest parts of these landslide areas is due to stream-generated erosion of the landslide toe and to decreased stability of the soil through saturation by groundwater. The upslope progression of soil displacement results in slope failure, which in turn undermines small landmasses in the shallow zone and causes further slope failure.

Introduction

In 2006, the U.S. Geological Survey (USGS), in cooperation with the Onondaga Lake Partnership and Onondaga Environmental Institute, began a 2-year study to determine the cause and progression of landslides in the two major tributary valleys to the Tully Valley. This report describes the landslides and their rate of movement, discusses the field methods, and interprets the probable causes of these landslides. It also includes geotechnical data from analyses of weathered and unweathered soil samples collected from both landslide areas and compares these results to previous geotechnical data analyzed from the floor of the Tully Valley.

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Tully Valley Study Area

The Tully Valley, near Tully, NY, is 6 miles long and forms the southern part of the Onondaga Creek valley, which extends 25 miles from the Tully Moraine through Onondaga Lake, near Syracuse (fig. 1). Unlike other valleys in the Finger Lakes region, the Onondaga Creek valley does not contain a lake but contained proglacial lakes when ice sheets advanced and retreated across the region between 1.6 million and 11,000 years ago (Rogers, 1991). The movement of glaciers widened and deepened the bedrock valleys of this region and, during their recession, left deposits of glacially derived sediment. As much as 400 feet of glacial (unsorted), lacustrine (lake-bottom), and fluvial (stream-related) deposits of clay, silt, sand, and gravel blanket the Tully Valley floor. The walls of the Onondaga Creek valley consist of Middle Devonian Hamilton Group shale and siltstone that gently dip to the south (40–50 feet per mile) and are covered with a thin layer of till.

Onondaga Creek flows northward through the Tully Valley, and two east-west trending tributaries—Rattlesnake Gulf on the west and Rainbow Creek on the east—enter the valley nearly opposite each other (fig. 1). These side valleys contain fine-grained lacustrine deposits laid down in side-valley glacial lakes that were impounded when the main ice mass occupied the Tully Valley.

Landslides in the Tully Valley

On April 27, 1993, the largest landslide in New York State since the early 1900s occurred on the west wall of the Tully Valley (fig. 1). The landslide covered about 50 acres and destroyed three homes; it also buried about 1,400 feet of Tully Farms Road (fig. 1) with 12 to 15 feet of mud and associated debris (Fickies, 1993; Pair and others, 2000). The probable causes of this landslide were twofold—slowly developing slope failure (movement) on the lower hillside, which was first reported 3 years earlier (Wieczorek and others, 1998), and increasing pore-water pressure within clay interbeds resulting

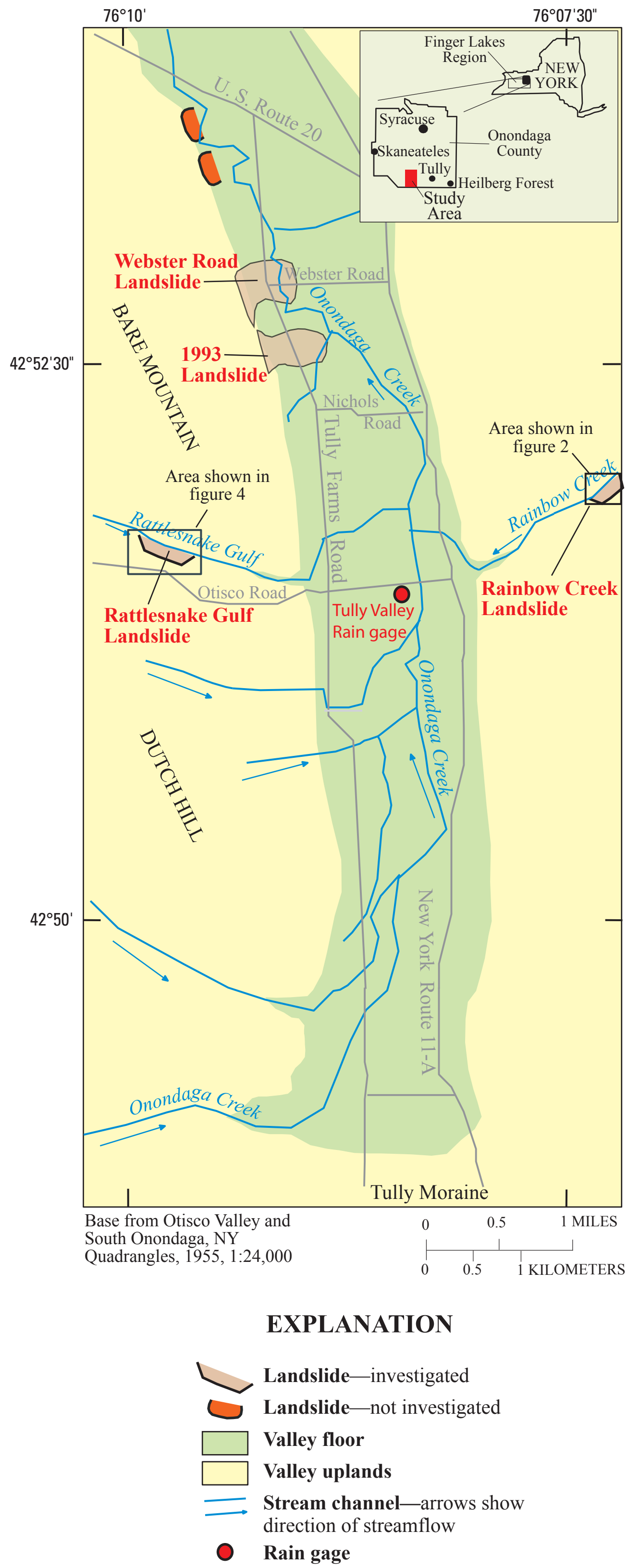


Figure 1. Physiographic features in the Tully Valley, Onondaga County, New York.

from rapid snowmelt from a record-breaking snowfall during the winter of 1992–93, followed by 7.5 inches of precipitation in early April 1993 (Pair and others, 2000). Several researchers evaluated the landslide shortly after it occurred, including Burgmeier (1998) and Morales-Muniz (2000), who completed geotechnical investigations of the landslide area, and Jäger and Wieczorek (1994), who constructed a landslide-susceptibility map of the Tully Valley and five adjacent valleys on the basis of clay distribution, former extent of proglacial lakes, and slope steepness.

Two much-older landslides, one overlying the other, were identified near Webster Road (fig. 1) just north of the 1993 landslide. These two slides were dated through Carbon-14 age-dating methods; the lower slide occurred about 9,800 Carbon-14 years before present (^{14}C yr B.P.) or 11,200 calibrated years before present (Cal BP years), and the overlying slide occurred about 6,100 ^{14}C yr B.P. or 7,000 Cal BP years ago (Pair and others, 2000; Kappel and Teece, 2007). The ages of two other suspected landslides further to the north have not been evaluated.

In 2005, an active, slow-moving landslide was found on the south side of the Rainbow Creek valley, and another was found on the south side of the Rattlesnake Gulf valley (fig. 1). The locations of these slides are consistent with the landslide-susceptibility map by Jäger and Wieczorek (1994). Soil displacement has occurred at both locations in the top layer of sediment (just below the root zone at the interface between weathered and unweathered soil) as small “islands” of soil and trees that slowly creep downhill then break loose and slide over the steep hillside into the stream channel.

Both of these slow-moving landslides are on north-facing, forested slopes that have been logged multiple times; the forest on the Rattlesnake Gulf landslide was selectively logged in 2007, and the forest on the Rainbow Creek landslide was last cut in the late 1990s. Average annual precipitation in this part of New York is about 40 inches per year, and the rainiest months are usually May, June, and July; monthly average precipitation for those 3 months is 3.5 to 4.0 inches. Soils are typically wettest before the trees ‘leaf-out,’ and after evapotranspiration has declined with plant dormancy (leaf-fall). Soil displacement and groundwater levels within the two landslides and precipitation on the floor of the Tully Valley between the mouths of the two streams were measured from the summer of 2006 through the summer of 2008.

Rainbow Creek Landslide

The Rainbow Creek landslide is on the southeastern slope of the creek (fig. 1); it was indicated by Jäger and Wieczorek (1994) to extend eastward along the creek from an altitude of about 800 feet at the creek to about 1,200 feet just west of the I-81 corridor (fig. 2). The active part of this landslide lies between altitude 840 and 950 feet and covers about 34 acres. The steep landslide surface faces northwest, and the material is primarily laminated clay and silt and well-sorted fluvial sand and gravel. The underlying bedrock on the valley slopes is stable, Middle-Devonian shale and siltstone of the Hamilton Group. Observations made throughout the summer and fall of 2006 indicated the landslide material consisted of more than 10 feet of laminated clay and silt overlain by 40 feet of interbedded, well-sorted silt, sand, and gravel that coarsen upward. This upper, interbedded material was rotated slightly upward from the horizontal position (fig. 3) and, after the 2006–07 winter, some of the sand and gravel unit had slumped into Rainbow Creek, exposing a scarp about 25 feet high that consisted of laminated silt and clay overlain by 8 feet of poorly sorted till. The layer of laminated silt and clay was also rotated from the horizontal—an indication that this layer was part of a larger landslide area. Smaller landslides of displaced material are evident on both sides of Rainbow Creek for at least 0.5 mile upstream (east of the present landslide area), and several landslide scars along the streambanks below the main landslide reveal the shale bedrock.

Groundwater discharges throughout the Rainbow Creek landslide, and several springs and seeps feed areas of standing water within the landslide scarps. Many of these ponded areas remain wet throughout the year, but the amount of standing water varies seasonally.

Rattlesnake Gulf Landslide

The Rattlesnake Gulf landslide is on the south slope of Rattlesnake Gulf Creek (fig. 1) and extends from an altitude of about 750 feet along the creek to an altitude of 1,250 feet (Jäger and Wieczorek, 1994). The active part of this landslide slopes steeply from altitude 740 to 850 feet and covers about 23 acres. Additional scarps and fractures extend to an altitude of 950 feet (fig. 4). Landslide material is mostly laminated silt and clay (fig. 5), although some well-sorted fluvial sand and gravel layers are exposed at several locations within the active landslide and are found covering the slopes above the landslide. As in the Rainbow Creek landslide, the silt and clay component is rotated from horizontal and overlies the stable Middle Devonian Hamilton Group shale and siltstone. Unlike the Rainbow Creek landslide, however, the Rattlesnake Gulf landslide does not have smaller, active components upstream from the main body, although several older landslide scars can be found upstream, and bedrock slides are seen on the north wall of the valley directly across from the active slide.

In January 2008, a test hole was drilled within the Rattlesnake Gulf landslide between small, active displacement scarps above the steep slopes adjacent to the stream. The stratigraphic log for this test hole (fig. 6) indicates the materials grade from sand and gravel to silt near land surface to fine sand and clay at depths below 20 feet. The bedding dips steeply near the surface, and the angle decreases with depth (fig. 6). The sediment color changes from reddish brown to grayish brown, and the bedding appears to be horizontal below a depth of about 70 feet. The shallow, rotated material appears to be similar to that in the main landslide area mapped by Jäger and Wieczorek (1994); the deeper sediments are not rotated and are not affected by past landslide movement.

Surface water at the Rattlesnake Gulf site drains mostly into two channels along the western and eastern edges of the active slide area; the flow in these channels varies seasonally in response to precipitation. Shallow groundwater appears as seeps and pockets of standing water within some of the displacement scarps of the slide.

Landslide Monitoring

Landslide-motion detectors (creepmeters) were constructed from old Stevens Type-F analog (paper and pen) water-level (drum) recorders (fig. 7) to record the timing and magnitude of land-surface displacement in both stream valleys. Land-surface displacement or movement measured at specific locations within a landslide cannot be used to compute displacement for the entire landslide but can be used to indicate relative movement and its timing within localized areas. Landslide displacement was further characterized by changes in the distance between an upgradient baseline tree and successive trees along a transect perpendicular to the active landslide slope.

Measurement of Precipitation and Groundwater Levels

Precipitation was measured hourly on the Tully Valley floor (fig. 1) between the Rattlesnake Gulf and Rainbow Creek landslide areas throughout the study by an automated tipping-bucket rain gage. Groundwater levels at each site were measured in 2-inch-diameter wells installed in August 2006 and augured to the unweathered-soil zone. A transducer was placed in each well to record the groundwater level every 15 minutes from August 2006 through June 2008.

Creepmeters

Creepmeters span active-displacement scarp fractures. The upgradient (and assumed stable) side of the scarp holds the creepmeters, which are attached by a cable to a firm object downgradient on the moving landmass, typically a tree. Creepmeters were installed at both landslides in June 2006 to record land-surface movement (soil displacement) at specific locations where movement was observed as ground cracks or as tilted or split trees. One creepmeter was installed along the steep, eroding slope of the Rainbow Creek landslide (fig. 2), and two creepmeters were installed at the Rattlesnake Gulf landslide—one to record movement along a new displacement scarp in the central part of the landslide, and the other about 1,500 feet to the northwest, along the steep, eroding slope above Rattlesnake Gulf (fig. 4). The cumulative displacement

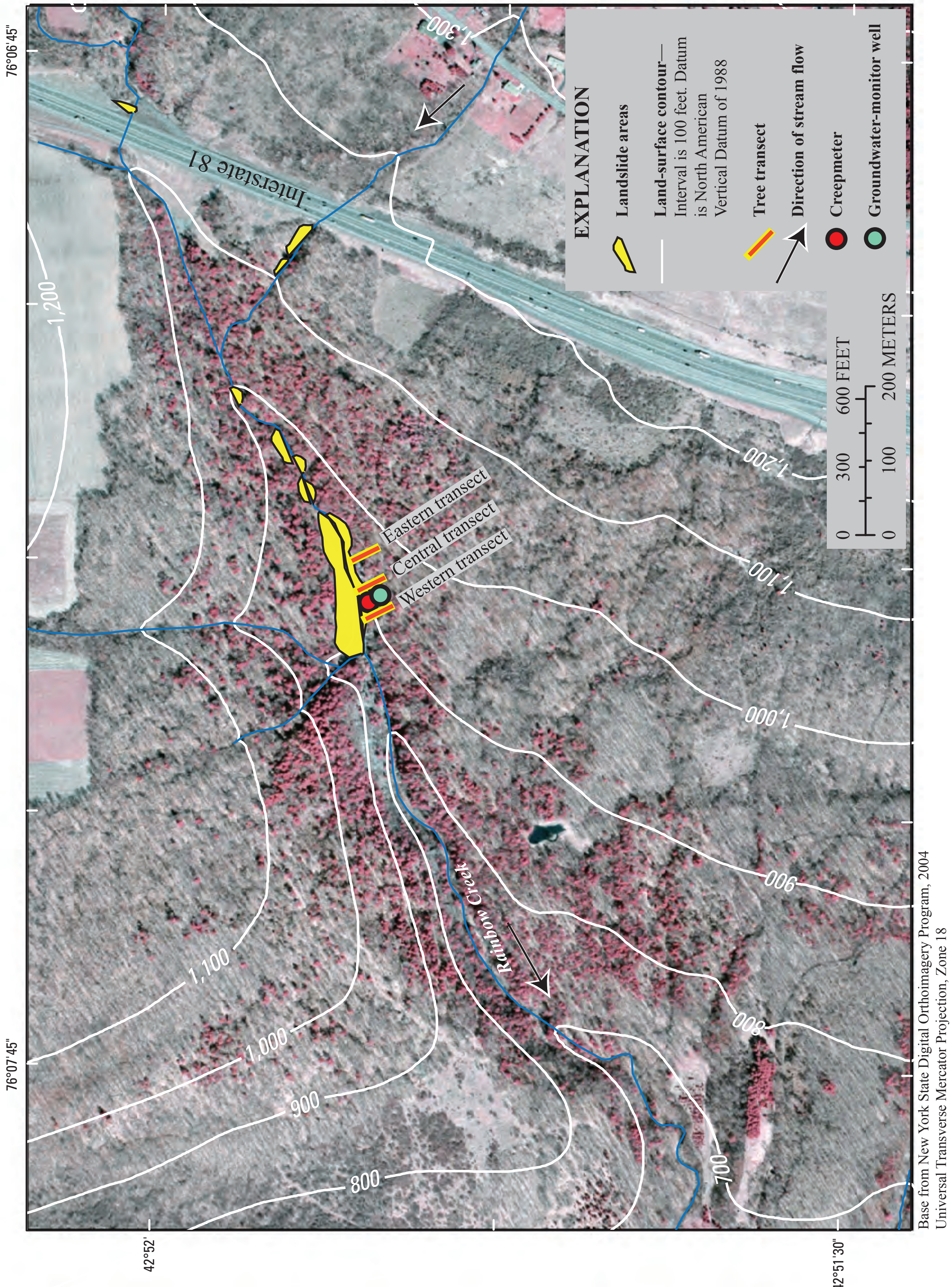


Figure 2. Rainbow Creek orthoimage with 100-foot contour lines, showing location of current landslide areas on the north and south sides of the Rainbow Creek valley, Onondaga County, New York. (Location is shown in figure 1.)

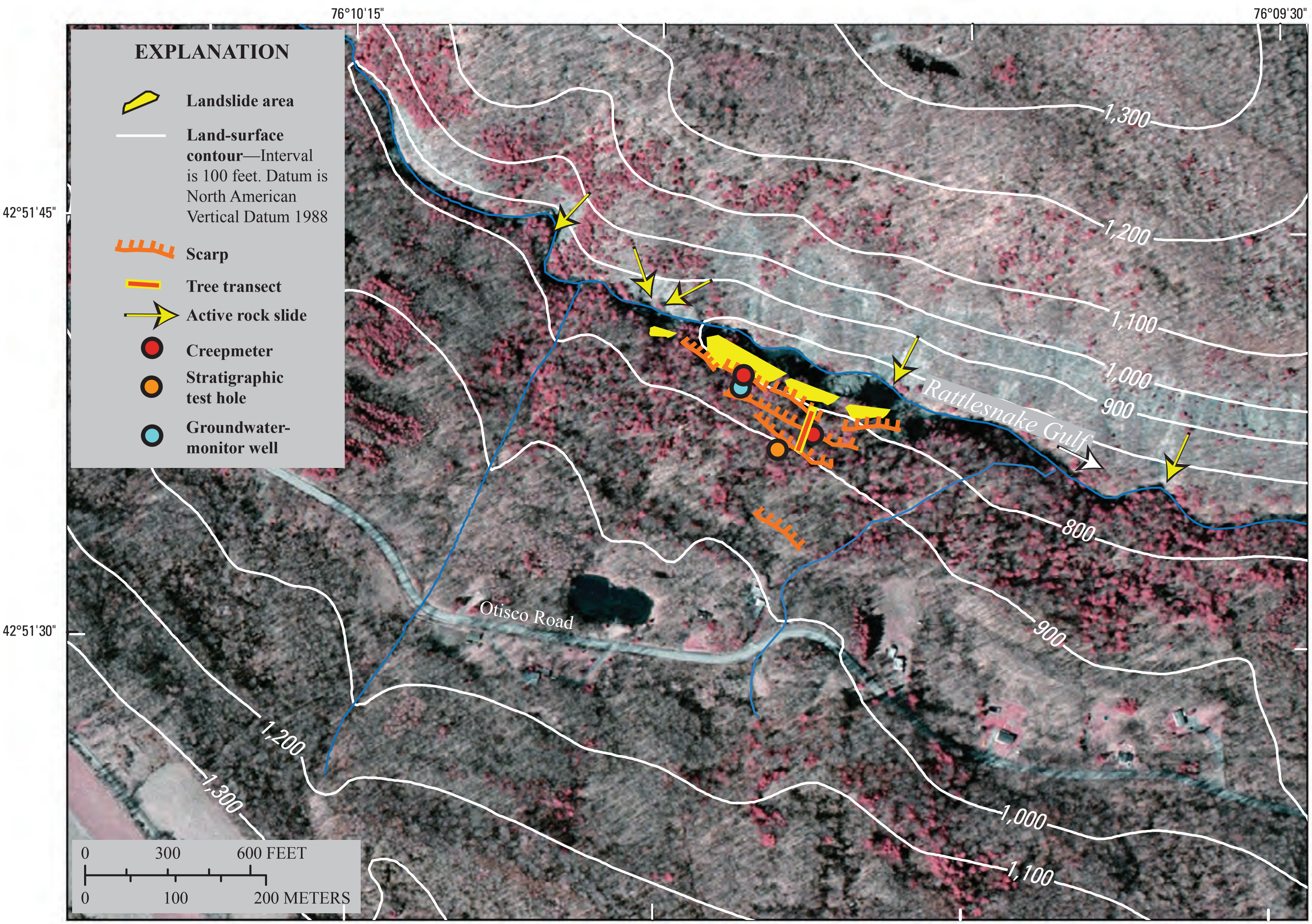
(Photo courtesy of Mark Schaub, Onondaga County Soil/Water Conservation District)

Figure 3. Hillside exposure of a rotated sand and gravel unit overlying fine-grained silt and clay in the Rainbow Creek landslide area, Onondaga County, New York. Photo is looking southeastward and side movement is toward the northwest (left in photo), toward Rainbow Creek.

values are plotted in figure 8 along with cumulative precipitation values and hourly groundwater levels.

From June 2006 through June 2008, the Rainbow Creek creepmeter recorded 1.2 feet of displacement during the first 16 months, after which the slope completely failed in November 2007 (fig. 8A). The northwest Rattlesnake Gulf creepmeter recorded 6.5 feet of total displacement, and the central Rattlesnake Gulf creepmeter recorded 3.5 feet of total displacement (fig. 8B). Slope displacement generally occurs in small increments on consecutive days, even during periods of the most rapid displacement (for instance, April 2008 at the northwest creepmeter, fig. 8B), but not all during one day, except when slope failure occurs.

From June 2006 through June 2008, the Rainbow Creek landslide showed little correlation between groundwater levels and slope displacement, other than the period of rapid groundwater rise in November 2007 that preceded the slope failure (fig. 8A). The creepmeter records for Rattlesnake Gulf indicate that movement at the northernmost scarp was greater than in the center of the landslide through the spring and summer of 2008. Although full-scale data collection had ended in June 2008, observations of slide movement continued at both slide areas through the end of 2008. The rate of movement increased in the central area of the Rattlesnake Gulf slide because of the slow, upward progression of slope failure and movement into the central part of this landslide, while during the same period of time the northwestern area did not move at all. The timing of slope displacement at the two creepmeters at Rattlesnake Gulf was similar through most of the study period, however, in that most of the movement



Base from New York State Digital Orthoimagery Program, 2004
Universal Transverse Mercator projection, Zone 18

Figure 4. Rattlesnake Gulf orthoimage with 100-foot contour lines, showing location of current landslide areas on the north and south sides of the Rattlesnake Gulf valley, Onondaga County, New York . (Location is shown in figure 1.)

occurred during periods of high groundwater levels and thus greater soil moisture than during dry periods with the exception of the central area during the fall of 2008.

Tree Displacement Transects

Three displacement transects were installed above Rainbow Creek (fig. 2), and one at Rattlesnake Gulf (fig. 4). Any change in distance between the trees reflects soil movement in response to active erosion at the landslide face. The baseline tree for each transect was assumed to be stable over the 2-year study period, but a new scarp developed on the Rattlesnake Gulf slide adjacent to the baseline tree in the spring of 2007 and may have caused this tree to move, or at least tilt, downslope. This movement may have affected the interpretation of the data along this transect, although the tree-displacement transect data from both sites supported the creepmeter data in indicating land-surface movement near the active scarp and further upslope.

Rainbow Creek Landslide

Most of the trees along the western-most transect were adjacent to an ephemeral and quickly eroding stream channel, and most of these trees were incrementally lost over a period of 3 to 5 months as the slope continued to erode rapidly. The other two transects (central and eastern) at this landslide indicated the upper slope was slowly responding (inches per year) to erosion of the landslide face. Most of the trees were moving apart (positive movement of one tree in the central transect is plotted in figure 9A), but some were moving closer to each other (negative movement of one tree in the eastern transect is plotted in figure 9B). The trees with negative movement tended to lean uphill; several of these trees were anchored by their roots to the stable, upslope land surface such that the movement of the unstable, underlying soil caused these trees to tilt uphill. Many of these trees were later lost through slope failure, which ripped the remaining anchor roots and sent the trees toppling down the steep slope of the landslide. The average rate of positive movement of all trees along these two Rainbow Creek transects was 2.1 inches per year.

Rattlesnake Gulf Landslide

Only one tree-displacement transect was established at the Rattlesnake Gulf landslide (fig. 4) because trees within the landslide area were being selectively harvested in 2006–07. This transect was within the central and more-active part of the slide and recorded mostly positive movement, including the baseline tree. The average rate of movement along this transect over the 2-year study was 1.8 feet.

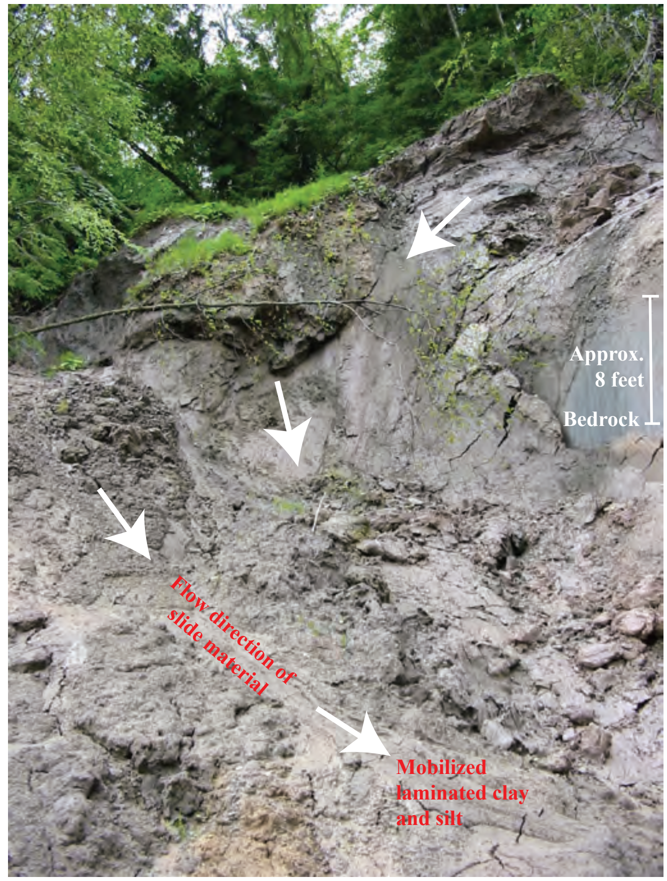


Figure 5. Slide materials in the Rattlesnake Gulf landslide area, Onondaga County, New York. View is looking south. (Location is shown in fig. 1.)

Precipitation

Total precipitation on the Tully Valley floor in the first year (June 2006 through May 2007) was nearly 43 inches and in the second year (June 2007 through May 2008) was 40 inches. Precipitation in this part of New York is fairly uniform over the course of the year, except for occasional, high-intensity storms.

Groundwater Level

Two-inch-diameter wells were installed at both sites in August 2006. The well at the Rainbow Creek landslide (fig. 2) was augered adjacent to the creepmeter through 2.75 feet of weathered, unconsolidated clay, silt, sand, and gravel to unweathered material (dense, fine-grained silt and clay with stones). The well at the Rattlesnake Gulf landslide (fig. 4) was installed along the northwestern landslide scarp and was augered through 5.8 feet of unconsolidated clay, silt, and sand before encountering the unweathered fine-grained silt-clay soil.

Rainbow Creek Landslide Photographs

Failure of upper scarp of sand and gravel, revealing laminated and tilted silt and clay unit with overlying till at Rainbow Creek landslide.

Toe of the slide area pictured above, showing debris flow and failure of opposite (north) slope of Rainbow Creek valley wall.

Rattlesnake Gulf Photographs

Slope failure which blocked Rattlesnake Gulf, late Winter, 2008, in the same area of the Spring 2006 slide pictured above.

Toe of slope failure which blocked Rattlesnake Gulf, Spring 2006

A split-tree found within the upper part of the Rattlesnake Gulf slide area.

Slope failure which blocked Rattlesnake Gulf, Spring 2006.

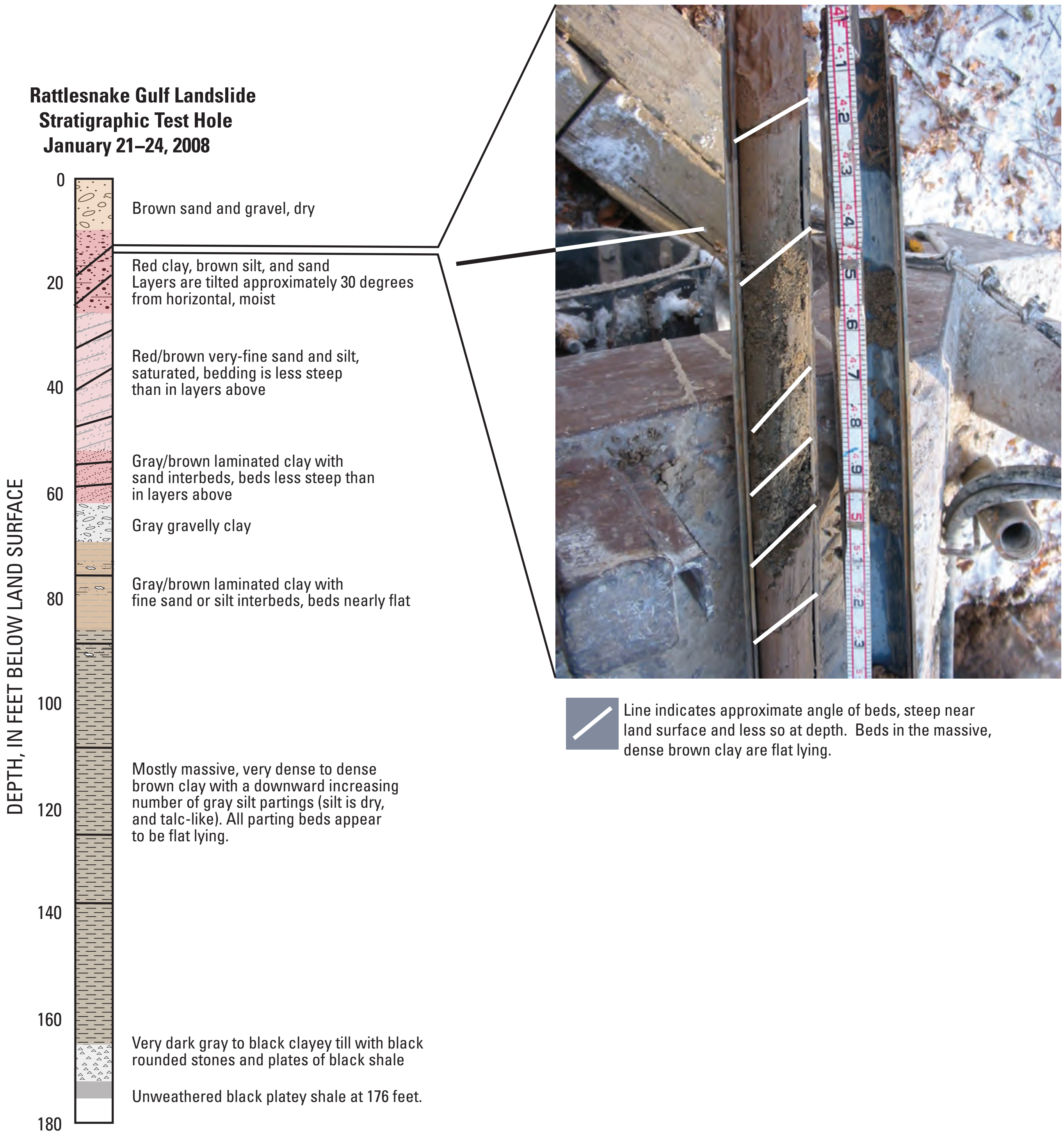


Figure 6. Stratigraphic log of unconsolidated sediment upgradient of active slide face at the Rattlesnake Gulf landslide area, Onondaga County, New York. (Location of test hole is shown in figure 4.)

Figure 7. Principal components of creepmeter used at Rattlesnake Gulf and Rainbow Creek landslide areas to detect and record rates of landmass movement.

Rainbow Creek Landslide

Groundwater levels at the Rainbow Creek landslide remained relatively stable from June 2006 through August 2007, after which they dropped and then sharply rebounded in mid-November 2007 (fig. 8A). The groundwater levels responded to individual precipitation and snowmelt events with little or no lag time. A perennial seep upgradient from the creepmeter and the well probably affected groundwater levels in this area and would account for the short lag time between a storm and a rise in groundwater level.

Rattlesnake Creek Landslide

Groundwater levels at the Rattlesnake Creek landslide generally fluctuated within a 1-foot interval, except from July through October 2007, when water levels sharply dropped more than 4 feet (fig. 8B). Groundwater levels appeared to respond to storms within 2 to 3 days. Groundwater seepage in slump areas on either side of the well indicates the water in this well comes from upgradient areas.

Landslide Activity in the Tully Valley Since the Late 1930s

The initial cause of the Rainbow Creek and Rattlesnake Gulf landslides is impossible to ascertain, but a review of aerial photographs from 1937, when the first aerial photos were taken in this part of New York State, indicate some landslide activity along the southern slope of Rattlesnake Gulf. Aerial photographs of the Rainbow Creek valley show no indication of landslides until the 1980s, although dense vegetation and the orientation of the photographs might mask earlier activity.

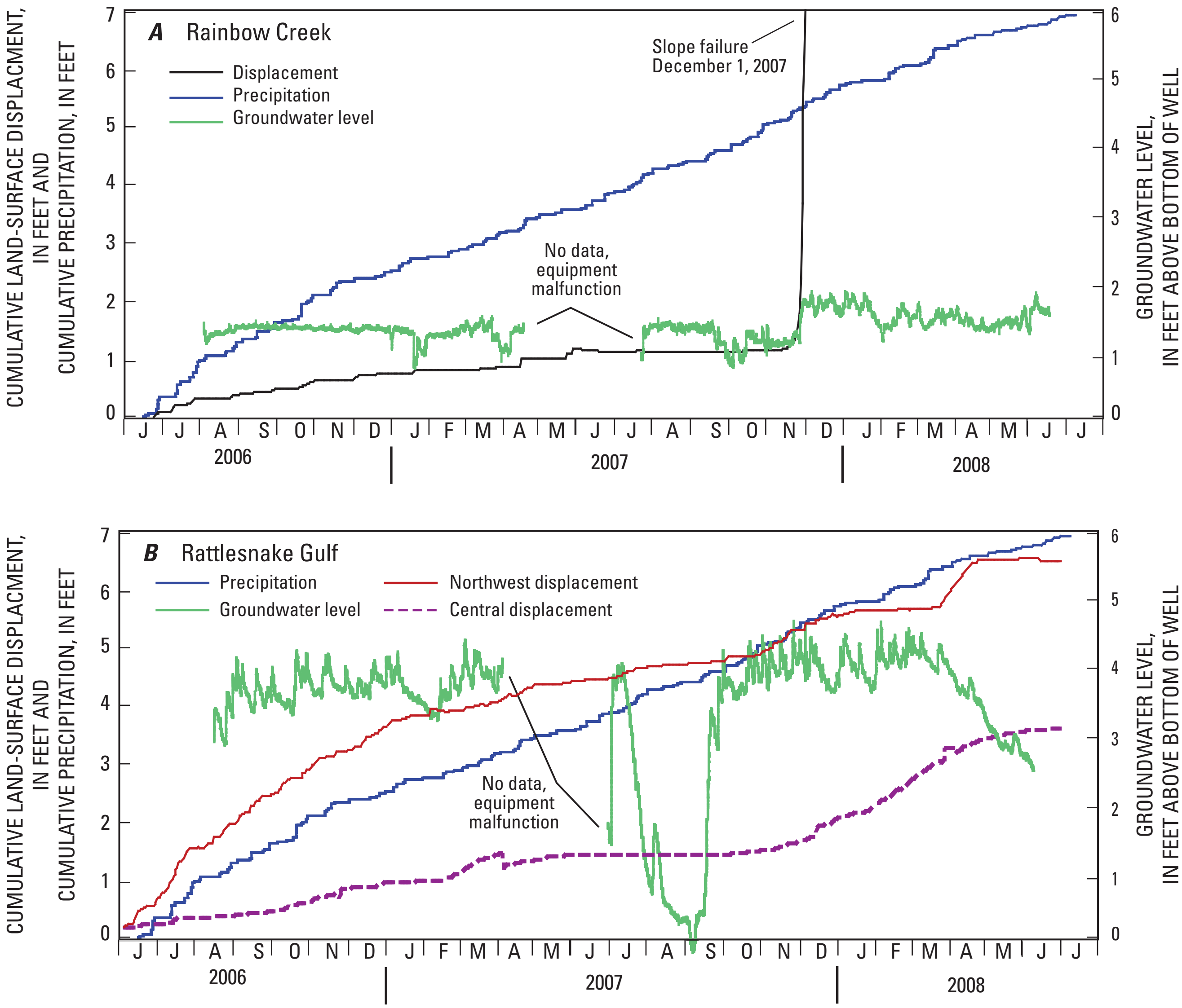


Figure 8. Cumulative creepmeter displacement and precipitation within the two landslide areas in relation to groundwater levels, June 2006 through June 2008: *(A)* Rainbow Creek site, and *(B)* Rattlesnake Gulf site. (Locations are shown in figures 2 and 4, respectively.)

A local resident who has lived next to Rainbow Creek most of his life reported that little landslide activity or sedimentation occurred in the Rainbow Creek channel along the eastern wall of the Tully Valley before the 1970s but recalled that a 30- to 40-foot waterfall over shale bedrock (fig. 10) just downstream from the current landslide area collapsed in the early 1970s. The resulting change in the stream channel could not be confirmed from the aerial photographs, but a narrow, 30-foot-high notch in the shale just downstream from the current landslide (fig. 10) marks the location of the former waterfall in the still-eroding stream channel. Coarse gravel, boulders, and fine-grained sediment behind (upstream from) this shale exposure are rapidly being eroded through the shale notch, causing an abrupt change in channel slope (generalized in figure 11) upstream from the former waterfall.

The account by this resident and the physical evidence of the waterfall location indicate that landslide activity here was initiated by (1) failure of the shale bedrock at the waterfall, (2) the subsequent steepening of the upstream channel bed as streambed material eroded and moved downstream after the waterfall collapse, and (3) destabilization of the steep, fine-grained slopes along both sides of the eroding stream channel upstream from the waterfall during high-flow periods.

Landslides in Relation to Precipitation and Groundwater Levels

Many factors can lead to landslides or can affect their extent and severity; among these factors are slope steepness, type of unconsolidated material, precipitation amount and intensity, hydrologic regime (streamflow characteristics), and water-table conditions. Individual storms can cause shallow slides of loose soil and rocks (Wieczorek and Sarmiento, 1988), whereas deep (rotational) slides of underlying material may not occur until days or months after a heavy storm (Varnes, 1978).

Rainbow Creek Landslide

The largest amount of movement at the Rainbow Creek landslide during the study occurred in November 2007, when the tree and landmass holding the measurement point for the creepmeter failed. The preceding summer was relatively dry, but several heavy storms in early November triggered a rapid rise in groundwater levels, which resulted in the displacement and eventual loss of the tree connected to the creepmeter. These November storms also caused a rapid increase in surface-water runoff, which quickly undermined the slope adjacent to the creepmeter landmass and contributed to the loss of the monitoring tree. Continued measurement of the remaining tree transects showed continued displacement along the upper slope of the Rainbow Creek landslide and the continued loss of trees on the remaining transects.

Rattlesnake Gulf Landslide

Several factors appear to have affected the landslide and soil displacement at Rattlesnake Gulf. The relatively rapid rate of soil movement at the location of the northwestern creepmeter coincided with wet months (fig. 8B), and the attendant rise in groundwater levels may have induced sliding as well as increased rates of stream erosion at the toe of the landslide below the creepmeter. In contrast, the center of this landslide is not adjacent to a major scarp but is upslope from an actively eroding landslide toe, and the displacement record for this central location (fig. 8B) suggests a longer response time for soil displacement here than at the northwestern location. For example, a large landslide in February 2008 blocked and continues to block the channel of Rattlesnake Gulf. As a result, land-surface movement is slowly propagating upslope to the center of the slide and was noted at the central creepmeter during the fall of 2008, even though groundwater conditions were relatively dry. This gradual upslope propagation of displacement from the stream channel and the movement of the baseline tree for the tree-measurement transect above the creepmeter support this hypothesis. The displacement and precipitation data (fig. 8B)

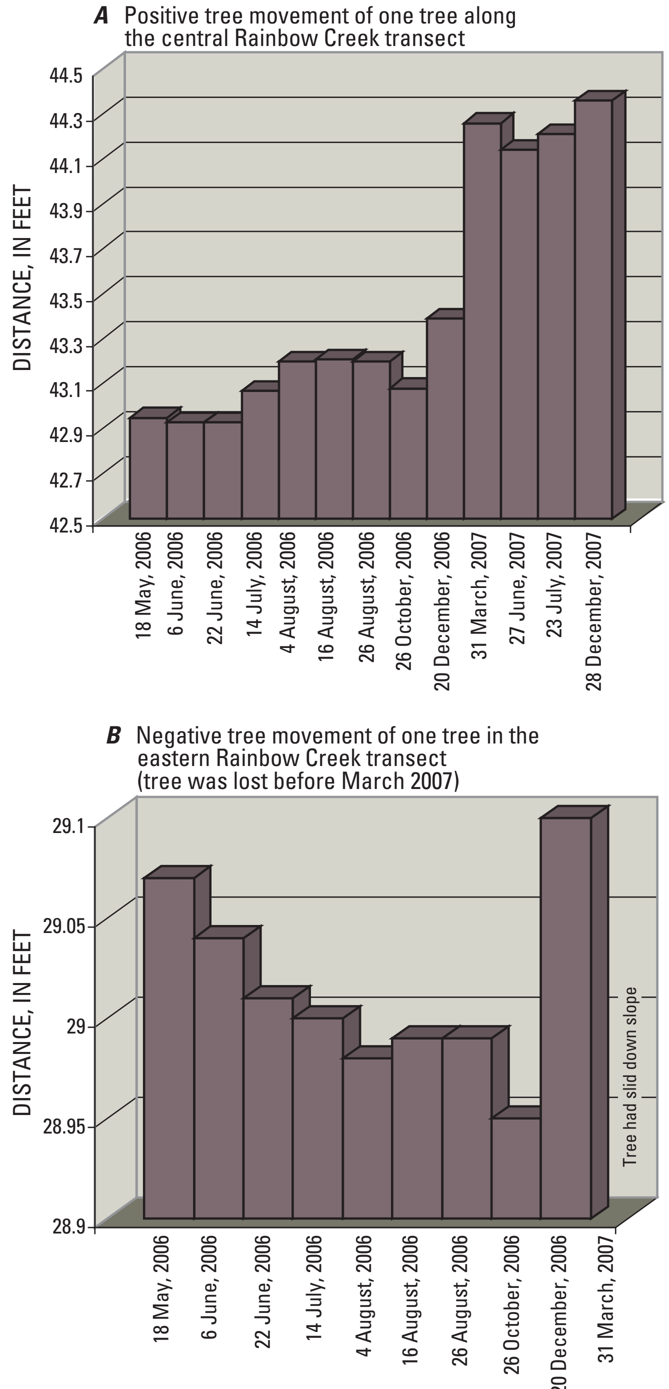


Figure 9. Tree movement along transects in the Rainbow Creek landslide area: *(A)* positive (increasing distance) movement, and *(B)* negative (decreasing distance) movement. (Note differing scales for 9A and 9B, and transect locations are shown in figures 2 and 4, respectively.)

Figure 10. Location of the former bedrock waterfall along Rainbow Creek, just downstream from the active landslide area.

also indicate, however, that shallow movement in the center of the landslide is facilitated by individual storms.

Except for the rapid slope failure at the Rainbow Creek creepmeter in November 2007, the northwestern Rattlesnake Gulf landslide scarp and the Rainbow Creek landslide scarp typically underwent the greatest displacement as the snowpack was melting and before tree 'leaf-out,' which are typically the wettest months of the year, during which the steep, unstable soils on these slopes become saturated. The coarse-grained sediment within the rotated, laminated clays and silts exposed along scarps and stream channels in both valleys may also provide a path for infiltration of water into the landslides.

Summary and Conclusions

Displacement of shallow soils at the Rainbow Creek landslide and the northwestern part of the Rattlesnake Gulf landslide was greatest during wet periods, and the largest displacement was at the Rainbow Creek creepmeter and in the northwestern part of the Rattlesnake Gulf landslide, probably as a result of the scarps above an unstable landslide toe that had been eroded by the adjacent stream. The center of the Rattlesnake Gulf landslide was most active after the failure of the lower slope; increased land-surface movement was noted at the centrally located creepmeter several months later. Groundwater levels at the weathered/unweathered soil interface of both landslides responded to precipitation and snowmelt within 2 or 3 days. Groundwater levels in scarps adjacent to the landslide toes were high in March 2007 in response to infiltration of snowmelt and spring precipitation. Displacement at the center of the Rattlesnake Gulf landslide may be facilitated by soil movement that begins at the toe of the landslide and may take several months to propagate upslope to the center of the landslide. Most of the soil material at both landslides is silt and clay, and the deeper, unweathered material at both sites has substantially less coarse-grained sediment than the weathered samples.

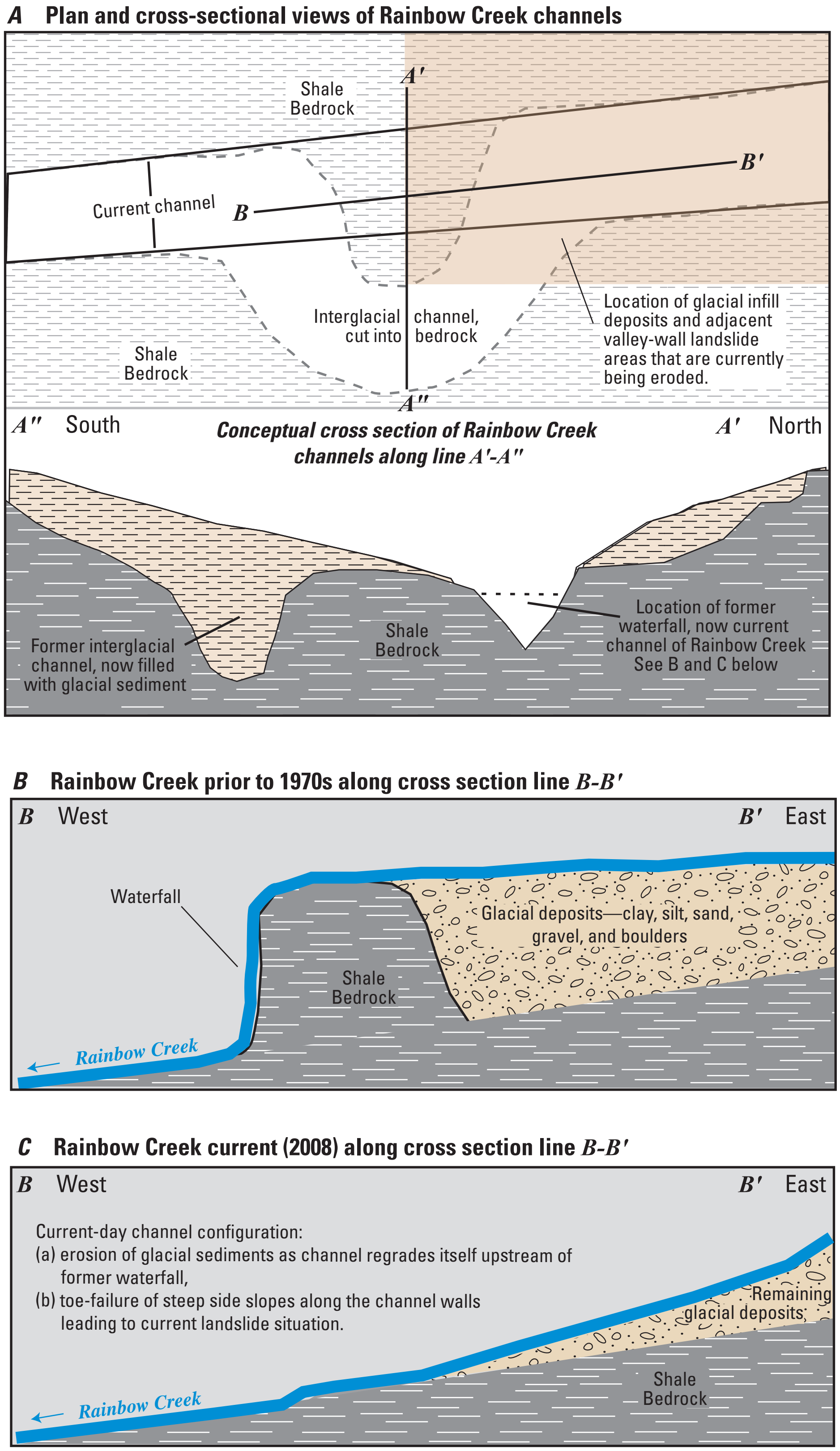


Figure 11. Conceptual progression of degradation of the Rainbow Creek channel behind the bedrock waterfall which initiated landslide activity: *(A)* plan view of the former and present stream channel with accompanying conceptual geologic sections through the two channels, *(B)* cross-sectional view (B–B′) of stream channel prior to failure of the waterfall, and *(C)* cross-sectional view (B–B′) of the stream channel in its current (2008) configuration, showing down-cutting of the glacial deposits that initiated ongoing landslide activity.

Geotechnical Properties of Rainbow Creek and Rattlesnake Gulf Landslide Soils

The geotechnical properties of soils provide an indication of the degree to which a soil is prone to movement. The Atterberg Limits test measures soil consistency in relation to its water content and defines the limits for four stages—solid, semi-solid, plastic, or liquid. A diagram of Atterberg Limits and indices is shown below.

Soils from the Rainbow Creek and Rattlesnake Gulf landslides were sampled in June 2007 for analysis of their geotechnical properties. Emphasis was placed on fine-grained soils (silt and clay) at each landslide because the strength of this type of sediment is a primary factor in landslide-failure analysis. Sediment-size distribution for weathered and unweathered fine-grained sediment from each slide is reported in table 1, and Atterberg limits and water content of each sample are reported in table 2.

The numbers from this study were compared with Atterberg-limit testing results from the 1993 Tully Valley landslide (Burgmeier, 1998) and with geotechnical data from samples collected 30 to 104 feet below the floor of the Tully Valley along Onondaga Creek near Nichols Road (Kappel and others, 1996). The results of these nearby studies (table 3) indicate the Atterberg limits for soils that blanket the side valleys are similar to those for soils on the Tully Valley floor. The only difference is the slightly greater water content for the valley-floor deposits, where the soils are saturated because the potentiometric surface within the clay is above land surface, whereas the landslide soils in the side-valley locations are partly drained.

Atterberg Limit Test
Stages of Soils Consistency

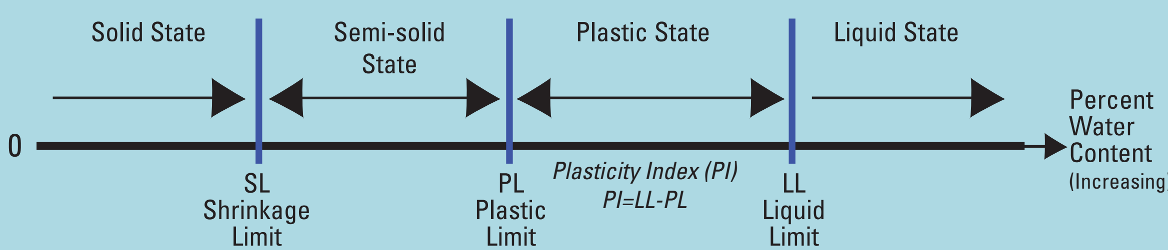


Table 1. Grain-size distribution of landslide sediment from Rainbow Creek and Rattlesnake Gulf, Onondaga County, New York.

Sample source	Type of material, as a percent of total soil mass			
	Gravel	Sand	Silt	Clay
		Rattlesnake Gulf		
Weathered soil	22	12	48	18
Unweathered soil	0	2	34	64
		Rainbow Creek		
Weathered soil	6	44	33	17
Unweathered soil	2	2	54	42
Landslide soil	28	17	32	23

Table 2. Atterberg limits and indexes for weathered- and unweathered-soil samples from Rainbow Creek and Rattlesnake Gulf, Onondaga County, New York.

Sample source	Water content (percent)	Plastic limit	Liquid limit	Plasticity index
		Rattlesnake Gulf		
Weathered soil	17.1	23	33	10
Unweathered soil	34.1	26	45	19
		Rainbow Creek		
Weathered soil	32.5	28	38	10
Unweathered soil	21.1	22	36	14
Landslide soil	8.9	18	32	14

Table 3. Average water content, plastic limits, liquid limits, and plasticity indexes for soil samples from Rainbow Creek, Rattlesnake Gulf, and Tully Valley in Onondaga County, New York .

Sample source	Average water content (percent)	Average plastic limit	Average liquid limit	Average plasticity index
Rainbow Creek landslide soil	26.8	25.0	37.0	12.0
Rattlesnake Creek landslide soil	25.6	24.5	39.0	14.5
1993 Tully Valley landslide soil	32.5	20.6	36.2	15.6
Tully Valley floor soil (composite)	32.7	23.4	37.2	13.8

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