

Prepared in cooperation with Onondaga Lake Partnership and  
Onondaga Environmental Institute

## Dendrogeomorphic Assessment of the Rattlesnake Gulf Landslide in the Tully Valley, Onondaga County, New York



Scientific Investigations Report 2009–5134

**Cover.** Left side picture—A small tree begins to split as the land on left side of the tree moves left, while the right side of the tree and its roots do not move—Rattlesnake Gulf landslide, Spring 2008.

Right side picture—Cross section of a hemlock tree showing asymmetric growth due to a landslide as the tree reorients its stem toward a vertical growth position.

Background picture—displays 'Jayed' trees at Rattlesnake Gulf landslide.

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By Kathryn L. Tamulonis and William M. Kappel

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## Conversion Factors, Datum, and Acronyms

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:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$$

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

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8$$

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
<sup>14</sup> C yr B.P.	Carbon-14 years before present
USGS	U.S. Geological Survey

# Dendrogeomorphic Assessment of the Rattlesnake Gulf Landslide in the Tully Valley, Onondaga County, New York

Kathryn L. Tamulonis<sup>1</sup> and William M. Kappel<sup>2</sup>

## Abstract

Dendrogeomorphic techniques were used to assess soil movement within the Rattlesnake Gulf landslide in the Tully Valley of central New York during the last century. This landslide is a postglacial, slow-moving earth slide that covers 23 acres and consists primarily of rotated, laminated, glaciolacustrine silt and clay. Sixty-two increment cores were obtained from 30 hemlock (*Tsuga canadensis*) trees across the active part of the landslide and from 3 control sites to interpret the soil-displacement history. Annual growth rings were measured and reaction wood was identified to indicate years in which ring growth changed from concentric to eccentric, on the premise that soil movement triggered compensatory growth in displaced trees. These data provided a basis for an “event index” to identify years of landslide activity over the 108 years of record represented by the oldest trees. Event-index values and total annual precipitation increased during this time, but years with sudden event-index increases did not necessarily correspond to years with above-average precipitation. Multiple-regression and residual-values analyses indicated a possible correlation between precipitation and movement within the landslide and a possible cyclic (decades-long) tree-ring response to displacement within the landslide area from the toe upward to, and possibly beyond, previously formed landslide features. The soil movement is triggered by a sequence of factors that include (1) periods of several months with below-average precipitation followed by persistent above-average precipitation, (2) the attendant increase in streamflow, which erodes the landslide toe and results in an upslope propagation of slumping, and (3) the harvesting of mature trees within this landslide during the last century and continuing to the present.

## Introduction

The Tully Valley represents the upper (southern) 6 miles of Onondaga Creek in Onondaga County, New York (fig. 1),

and has had a history of landslides (Pair and others, 2000; Fickies, 1993; Jäger and Wieczorek, 1994). Two of its tributary valleys—Rainbow Creek and Rattlesnake Gulf—drain forested uplands and enter the main stream from the east and west, respectively; each tributary valley contains an area with active landslides (fig. 1). The landslide material within the western tributary valley, Rattlesnake Gulf (the focus of this report), covers 23 acres and consists of unconsolidated, laminated, glaciolacustrine clay and silt that has undergone massive movement and (or) rotation in the past. Information on the age and history of this landslide would provide a basis for interpretation of current landslide processes and possibly could be used elsewhere in the Tully Valley.

A technique commonly used to study landscape evolution that occurs through such processes as floods, landslides, and debris flows (Sigafoos, 1964; Hupp, 1983; Hupp and others, 1987) is dendrogeomorphology, a term derived from dendrochronology, the science of dating changes in the environment through tree-ring analysis, and geomorphology, the science of landform configuration and change. Dendrogeomorphology is based on the premise that landmass movement, expressed as slope failure, can cause trees to tilt, which in turn can trigger a response in tree growth that is seen as an alteration in the thickness of new wood added around the trunk yearly to compensate for the shift away from vertical. The tree rings formed during the years in which tilting occurs are thicker on the downward facing side (of hemlock trees in this study) rather than on the upward facing side, and this asymmetry indicates the years in which the land movement occurred. Therefore, the dendrochronology of the Rattlesnake Gulf landslide may provide information on soil movement within this landslide during the life of the oldest trees, which have stood for more than 100 years, and supports geomorphic evidence gained from nearby landslide studies that the development and movement of a landslide are determined by a combination of environmental factors. For example, a rise in groundwater levels from prolonged precipitation increases pore-water pressure in clay interbeds and may thereby facilitate soil movement on affected slopes (Hupp, 1983; Pair and others, 2000; Lollino and others, 2002; Lollino and others, 2006). The increased pore-water pressure in landslides in response to rising groundwater may occur immediately or it may lag by hours to several days (Lollino and others, 2006) or

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by months to years (Ibsen and Casagli, 2004), depending on the geology and hydrology of a particular site.

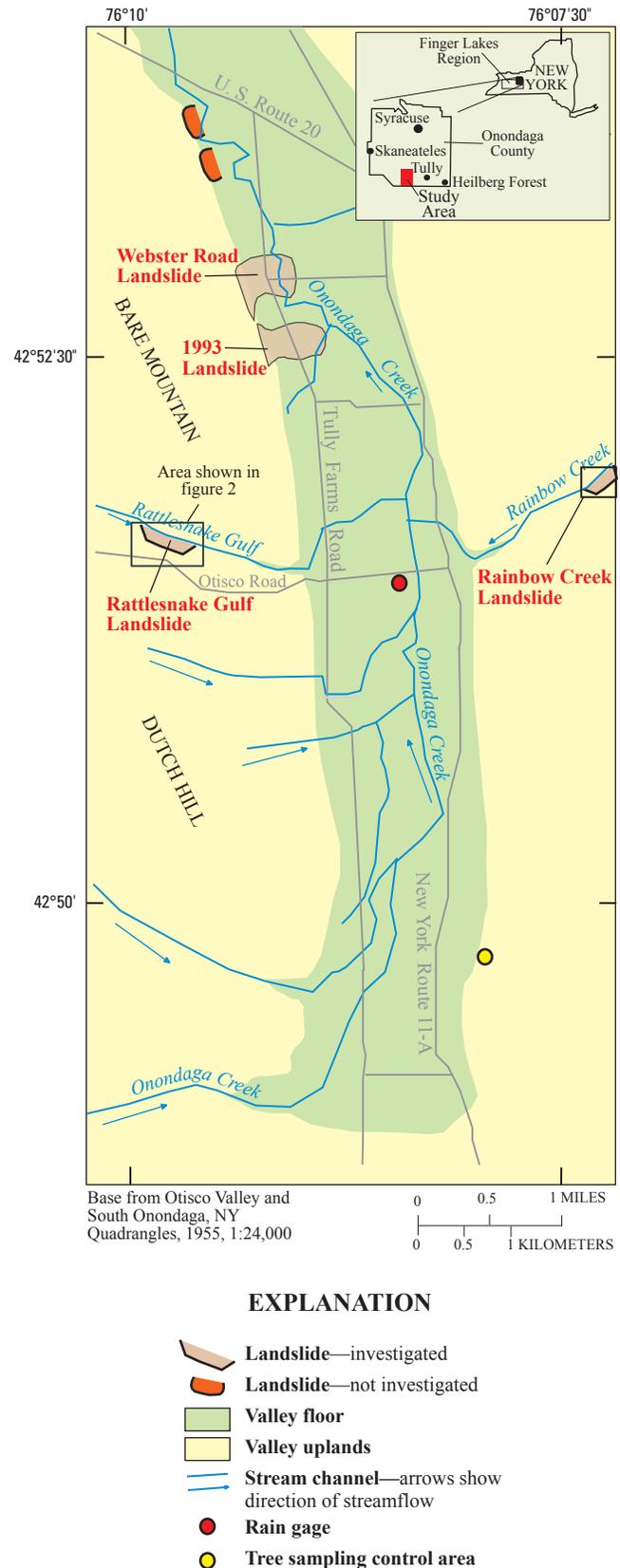
Estimation of the potential for current and future landslide activity at this and nearby locations requires information on (1) the frequency and severity of landslides as indicated by the tree-ring analyses, (2) the composition of the soils (weathered and unweathered) that form the landslide material, and (3) interaction among precipitation, groundwater levels, and the landslide material.

In 2006, the U.S. Geological Survey, in cooperation with the Onondaga Lake Partnership and the Onondaga Environmental Institute, began a 2-year study to evaluate the cause and progression of landslides in two tributary valleys to the Tully Valley. This report (1) describes the physiographic setting of the Rattlesnake Gulf landslide and the geomorphic processes that shaped it, (2) explains the application of dendrogeomorphic techniques to interpret the history of the slide during the last century, and (3) summarizes the probable causes of landslide movement at this location.

### Physiography of the Tully Valley

The Tully Valley is a 6-mile-long glacial trough at the head of Onondaga Creek, which flows 15 miles northward to the city of Syracuse (fig. 1). Multiple glacial advances and retreats between 1.6 million and 11,000 years ago (Rogers, 1991) widened and deepened the river valleys of New York and left behind deposits of clay, silt, sand, gravel, and till of varying thickness on the sides and floors of these valleys (Kappel and Miller, 2003). The last major ice advance in central New York was about 14,000 years before present (B.P.), and its eventual retreat northward about 11,000 years B.P. resulted in the deposition of unconsolidated material that blocked the southern (upper) ends of the river valleys. Glacial meltwater filled these valleys to form proglacial lakes; layers of silt and clay gradually accumulated on the floor of these lakes, and streams of meltwater from the retreating ice deposited a variety of sediments along the floors and sides of the tributary valleys. One of these tributary valleys is the Rattlesnake Gulf valley, about 5 miles northwest of the village of Tully (fig. 1).

In April 1993, the largest landslide in New York since the early 1900s occurred on the west wall of the Tully Valley (Fickies, 1993; Pair and others, 2000) (fig. 1). Debris from this landslide covered about 50 acres and destroyed several homes (Pair and others, 2000); it also buried a 1,400-foot length of Tully Farms Road (fig. 1). Evidence of two other landslides, one overlying the other, was found just north of the 1993 landslide near Webster Road (fig. 1); the lower landslide has been dated at 11,200 calibrated years before



**Figure 1.** Physiographic features of Tully Valley, Onondaga County, New York.

present (Cal BP years)<sup>1</sup>, and the other at 7,000 Cal BP years (Kappel and Teece, 2007). These slides are much older than the Rattlesnake Gulf landslide and the process of landslide movement appears to be much different in regard to their geographic position at their respective locations.

## Rattlesnake Gulf Landslide

The Rattlesnake Gulf landslide is on the south slope of Rattlesnake Gulf and covers about 23 acres (fig. 2). An older, larger landslide lies between altitudes 1,250 and 750 feet on the south slope of Rattlesnake Gulf (Jäger and Wiczorek, 1994), and several landslide scars are visible on the bedrock wall of the north slope, directly opposite the active landslide. The current landslide, between altitudes 950 and 740 feet, consists primarily of rotated, laminated silt and clay that dips steeply to the southwest. The clay was deposited in a proglacial lake that occupied the Rattlesnake Gulf Valley west of the glacial ice mass in the Tully Valley.

Shallow-soil displacement (movement) occurred adjacent to a steep scarp on the northwest side of the landslide area, and shallow displacement and slump propagation from the toe of the slide upwards into and beyond the central part of the landslide occurred during this study (July 2006 through June 2008) (fig. 3). Groundwater levels were recorded adjacent to the scarp during that time, and precipitation data were collected from a rain gage on the floor of the Tully Valley (fig. 1). The shallow-soil displacement roughly coincided with snowmelt and rainstorms and with the attendant rises in groundwater levels that lagged these precipitation events by as much as 2 days (Tamulonis and others, 2009).

Shallow-soil displacement is greatest in the northwestern part of the landslide, where scarps are oversteepened as a result of erosion by the stream. Shallow-soil displacement at the center of the landslide area may be facilitated by sustained high groundwater levels as well as by the slow upslope propagation of shallow stress release from the toe of the slope up and into the center of the landslide (Tamulonis and others, 2009).

Surface water in the landslide area drains mostly into two channels along the western and eastern sides of the landslide where discharge varies seasonally. Groundwater also collects in depressions along scarp areas and within the slide mass. The water table at a monitoring well installed on the northwestern scarp of the landslide (fig. 2) averaged less than 2 feet below land surface during the study.

Forest cover at the site is mostly oak (*Quercus* L. sp.) and maple (*Acer* L. sp.); the understory is mostly Eastern hemlock (*Tsuga canadensis*) and tulip poplar (*Liriodendron tulipifera*). The landslide area has been logged in the past and

was selectively cut in 2007. Average annual precipitation, as recorded at long-term meteorologic stations at Skaneateles, NY, and Tully Forest, NY (both within a 16-mile radius of the study site), is 40.2 inches per year, and the wettest months are usually May, June, and July, when monthly average precipitation is 3.5 to 4.0 inches.

## Tree Sampling and Data Collection

Tree-ring widths from 18 sampled trees in the landslide area and from 12 trees in 3 control areas—near the Rattlesnake landslide, near the Rainbow Creek landslide across the valley, and near the southeastern end of the Tully Valley (fig. 1) were measured, and comparisons of reaction-wood thickness were made to identify the years of growth-rate change at the landslide. Further information on reaction wood is given in the “Geotropism and Reaction Wood” section on page 12.



Another split tree adjacent to the Split-Tree Creepmeter. This tree split apart in the early 1970s, but did not fully separate. The tree was still alive (2007) and the wound was healing.

<sup>1</sup> “Calibrated years before present” (Cal BP years) reflects changes in Carbon-14 concentrations in the atmosphere over the last 40,000 years and corrects for these changes, thereby generally increasing the radiocarbon-based age to Cal BP age, in years before present.

### Landslide Movement at Rattlesnake Gulf at the Split-Tree Creepmeter Site



April 2006 approximately 2 ft



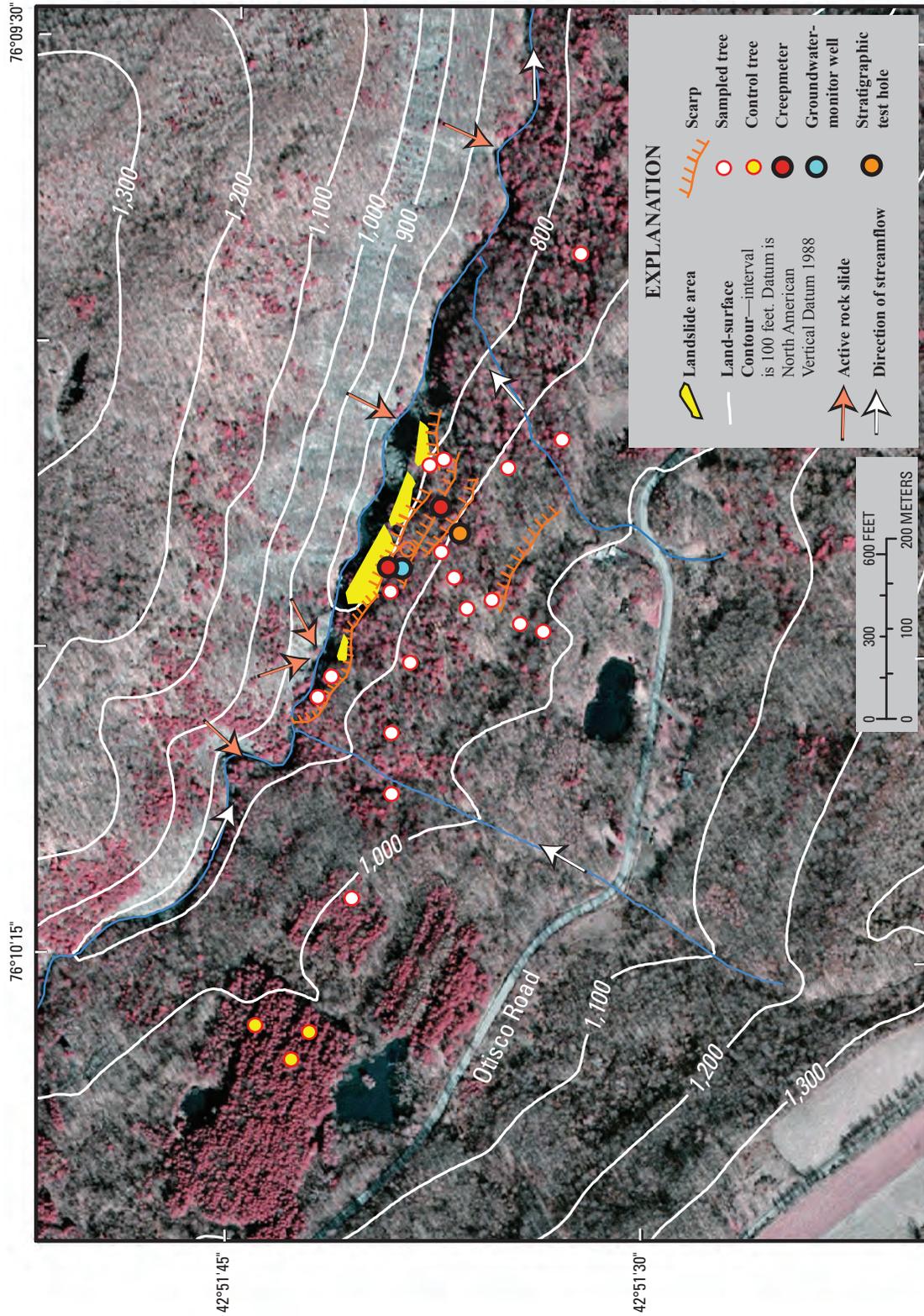
September 2006 approximately 4.5 ft



July 2006 approximately 3.5 ft

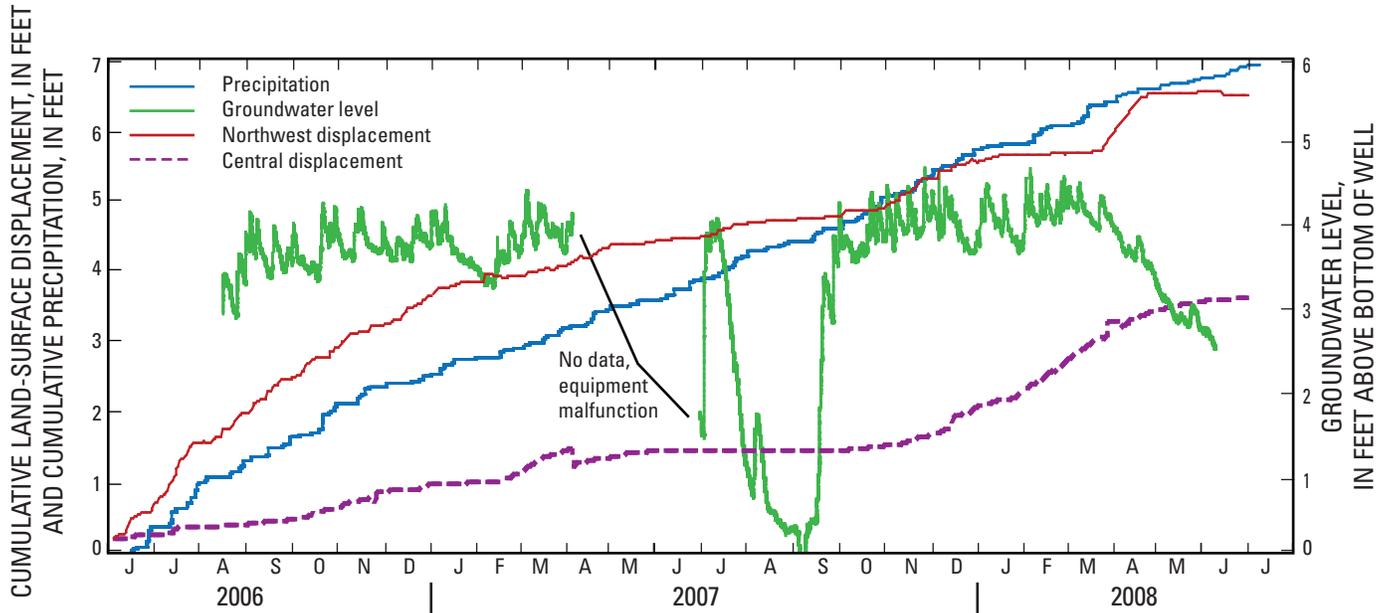


September 2007 approximately 6 ft  
(Arrows indicate each half of the tree.)



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

**Figure 2.** Rattlesnake Gulf orthoimagery with 100-foot contours, showing the location of current landslide areas, scarps, sampled trees, creepmeters, and a groundwater-level monitoring well in Onondaga County, New York. (Location is shown in figure 1.)



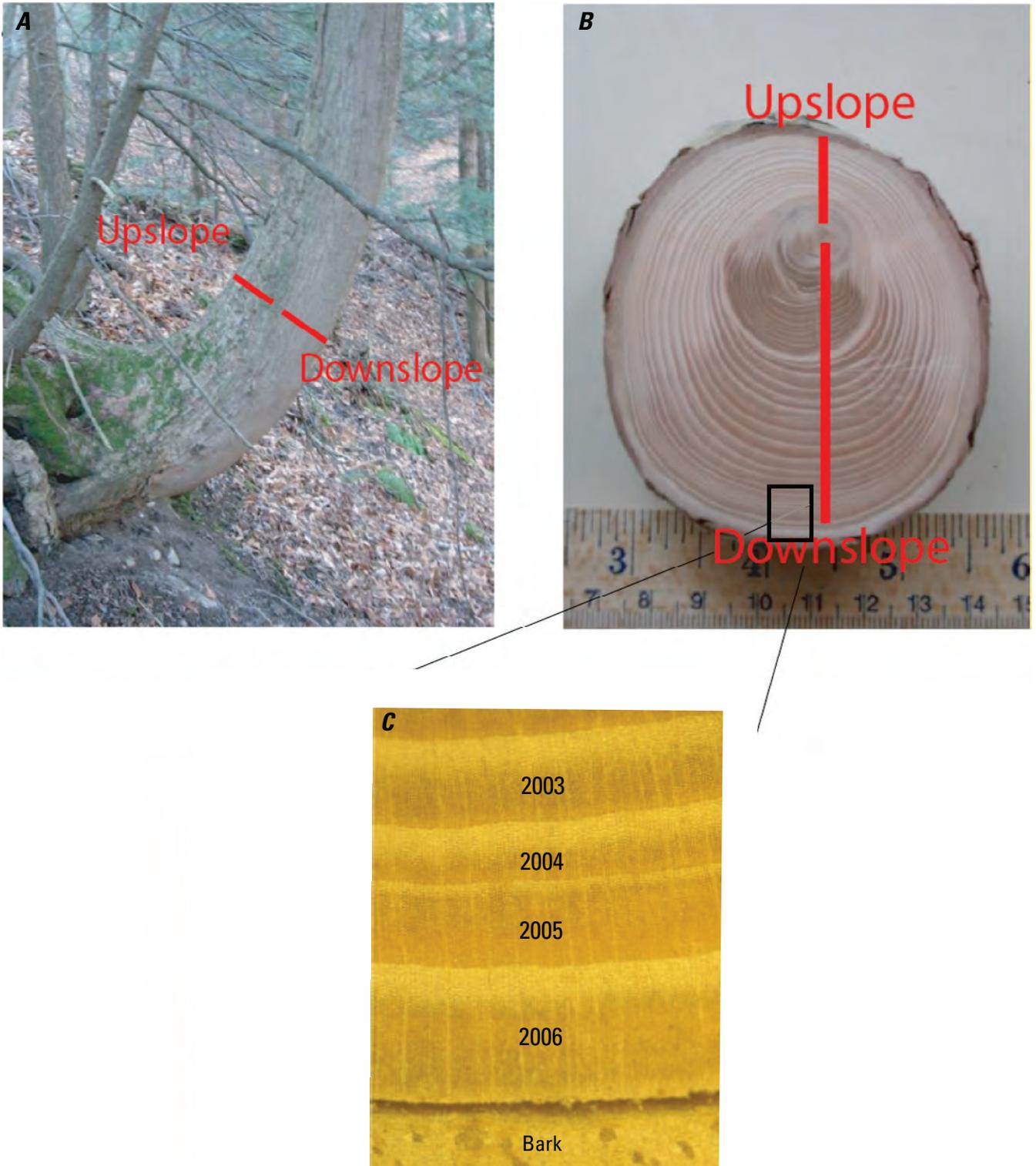
**Figure 3.** Cumulative creepmeter displacement and precipitation in relation to groundwater level within the Rattlesnake Gulf landslide area from June 2006 through June 2008. (Location shown in fig. 2.)

## Methods

A total of 34 increment cores and tree sections were collected from 18 *Tsuga canadensis* sp. (Eastern hemlock) trees within the landslide area. Sample-collection transects were made parallel to the active-landslide slope and perpendicular to it (fig. 2); trees with visible bends in the trunk (an indication of soil movement) were also sampled, regardless of their location. Samples from affected trees were collected at the bend in the trunk, where reaction-wood growth (fig. 4) was expected to be greatest, and samples from trees not obviously affected by soil movement were collected 4.5 feet above the ground. Of the 30 trees sampled, 13 had visibly tilted trunks; the remaining 17 did not. Trees disturbed by other processes, such as wildlife browsing, tilting from the weight of fallen trees, or human factors such as vehicle damage during timber harvesting, were not sampled, although the presence of such disturbance indicates that factors other than landslides may have caused some of the tilting. Generally, two increment borings (pencil-size cores) were collected from each tree—one on the upslope side, and one on the downslope side. In addition, an entire cross section was recovered as a continuous core from one tree and one entire cross section was collected from another tree because a complete cross section reveals the asymmetry of the tree-ring pattern, as well as differences in tree-ring widths from one radius to the next throughout the section, and thereby provides a more reliable record of disturbance than the cores alone (Potter, 1969).

In addition, increment cores were collected from each of 12 control trees [*Tsuga canadensis* sp.] from 3 different control sites; 3 of these trees (8 cores) were adjacent to the Rattlesnake landslide, and 3 additional trees (8 cores) were collected adjacent to the Rattlesnake landslide in areas with surface slopes of less than 10 percent (fig. 2). The other 6 control trees (12 cores) were collected in a forested area 6.5 miles from the study site in the southeastern part of the Tully Valley (labeled “control area” in fig. 1). These six control trees were on a steep slope similar to that of the landslide, but the thin soils that blanket that slope are underlain by apparently stable shale bedrock. Trees growing on slopes typically have asymmetrical (“eccentric”) growth patterns that are probably unrelated to surface displacement, but rather reflect the natural response to the slope itself and also to shade cast by neighboring trees (Phipps, 1974). Abrupt shifts in tree-ring eccentricity, however, are likely to be indicative of slope movement. Therefore, the purpose of the control trees was to distinguish eccentricity caused by non-landslide causes from that associated with soil displacement.

Core analysis entailed surface sanding to provide a clear surface for measurement of tree-ring (increment) thickness (resolution to 0.01 millimeter) on an increment-measurement machine under a binocular microscope with Corina software (Cornell University, 2008a). Each increment-core sample was measured twice, and duplicate measurements with greater than 3-percent discrepancy and cores with missing rings, were cross dated (Cleaveland, 1980) through comparison of a third measurement with the values from other samples (Cornell



**Figure 4.** Tree affected by soil movement at the Rattlesnake Gulf landslide, Onondaga County, New York: (A) 'J'-shaped profile of the tree and up- and down-slope sampling locations, (B) ring and reaction-wood growth pattern, which creates the 'J'-shaped tree trunk, and (C) reaction wood on the downslope side of a tree representing years 2003–06 growth.

University, 2008b). Ring widths in cores from upslope and downslope sides of the same tree were plotted together. The date of the oldest tree ring, as indicated by both cores from a single tree, was A.D. 1877.

Reaction-wood growth and tree-ring eccentricity were the main indicators used in this analysis because the landslide is relatively slow moving. A ring-width ratio (larger width divided by the smaller width) was calculated for every year of each core sample for each tree, including the control trees. Of the 14 control trees, 9 had a ring-width ratio greater than 2, and none had a ratio greater than 3; therefore, a ring-width ratio greater than 3 was designated to distinguish landslide activity from normal hillside creep to which the control trees were probably exposed (Phipps, 1974). Years in which trees within the landslide area had a ring-width ratio of at least 3 were considered to be years when the tree moved (tilted) in response to some form of landslide movement. The largest ring-width ratio for any tree at the landslide was 77.7.

Shallow-soil-displacement data by creepmeter and tree-displacement transects collected in a companion study (Tamulonis and others, 2009) within the landslide indicate the landslide surface is moving continuously, although slowly (inches per year). The ring-width ratios, which represent many decades of tree growth, are consistent with continuous movement, as described by Phipps (1974), rather than

indicative of a single, large event with progressive recovery of trees to a near-vertical position. This continuous movement is also supported by the presence of reaction-wood growth on both the upslope and downslope sides of individual trees within the landslide area. The presence of reaction wood in upslope cores of evergreen trees can be attributed to upslope tilting and was found in several of the landslide-area trees, whereas reaction wood on the downslope side is indicative of downslope movement, which is found in most of the trees within the slide area. It should be noted though that not every year with a ring-width ratio greater than 3 has reaction-wood growth.

### Event-Response Curve and Precipitation Data

An “event-response curve” (graph) of tree-ring data was first used by Schroeder (1978) to analyze landslide-movement frequency over time. The event (a landslide or soil displacement) causes a response (change in tree-ring growth pattern) in effected trees within a landslide; thus, the years indicated by anomalous tree-ring thickness can be plotted to reveal the timing of the displacement. Several studies worldwide have used this method to estimate the timing of debris flows and landslide displacement and to date historic avalanches (Bollschweiler and others, 2006; Stefanini, 2004; Potter, 1969). A difficulty with the Rattlesnake Gulf data is that timber harvesting in the landslide area since the late 19th century has decreased the number of old trees (and hence the amount of event-response data) backward through time and thereby decreased the numbers of early samples available. The earliest tree-ring indication of landslide activity was in 1877, but few trees dating from that period were available. The need for at least two trees (four sample cores) reflecting an event resulted in a starting date of 1899 for the Rattlesnake Gulf event-response curve, rather than 1877 (fig. 5A).

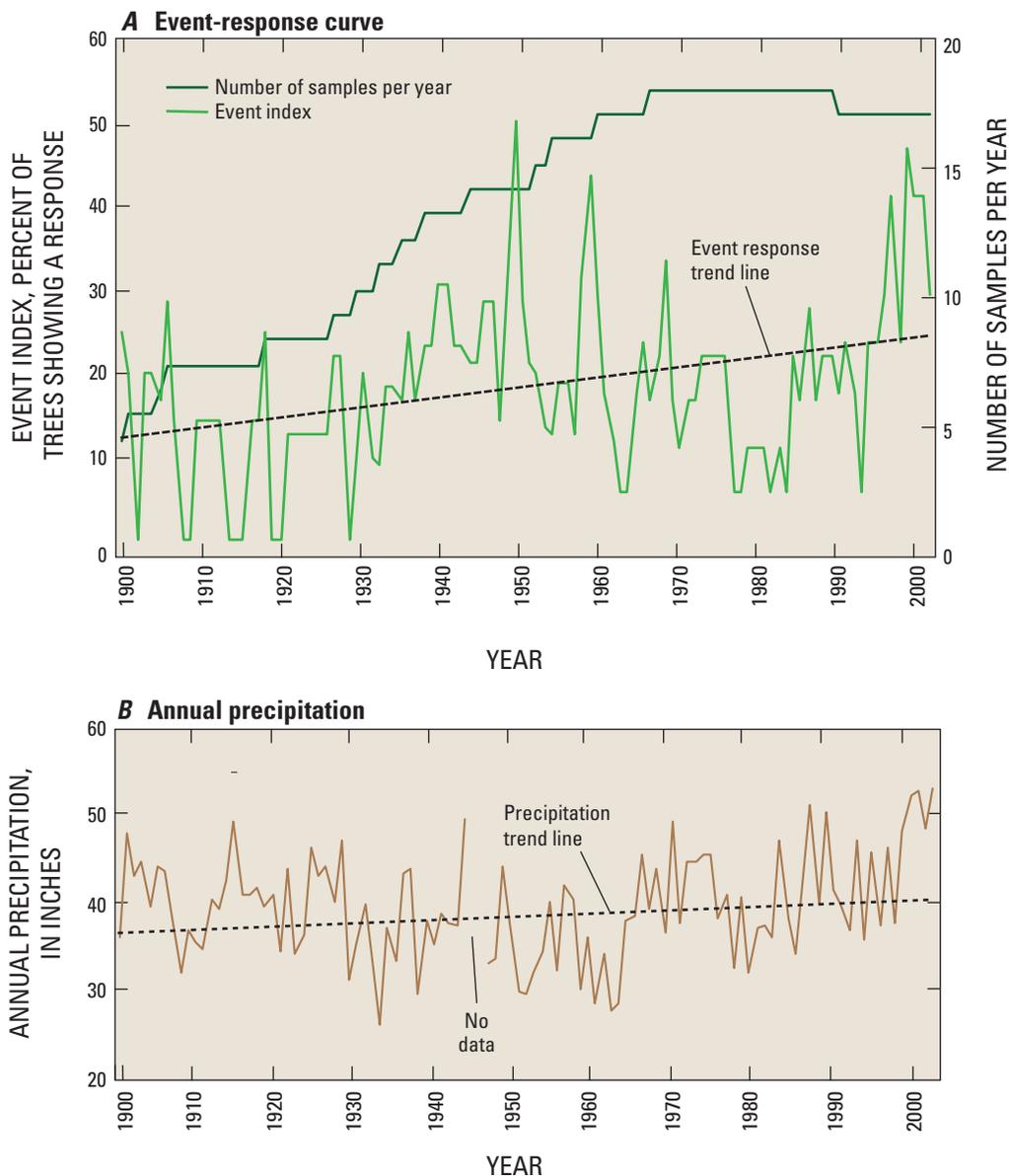
The graph of annual precipitation through time (fig. 5B) is based on data from two long-term meteorological sites rather than from the floor of the Tully Valley, which only has a 15-year precipitation record. Precipitation data from 1900 to 1997 were recorded at Skaneateles, NY, 16 miles northwest of the study area, and data from 1998 through 2007 were recorded in Tully Heiburg Forest, 8 miles southeast of the study site. Linear-regression trend lines for annual precipitation data were calculated through a least-squares fit and indicate a slight upward trend over the 107-year period of record (fig. 5B).

### Historic Landslide Activity in Relation to Precipitation and Timber Harvesting

The Rattlesnake Gulf event-response curve (fig. 6A) indicates that the number of years without landslide activity (those years with an event index of zero; that is, no tree-ring



Example of Jayed trees

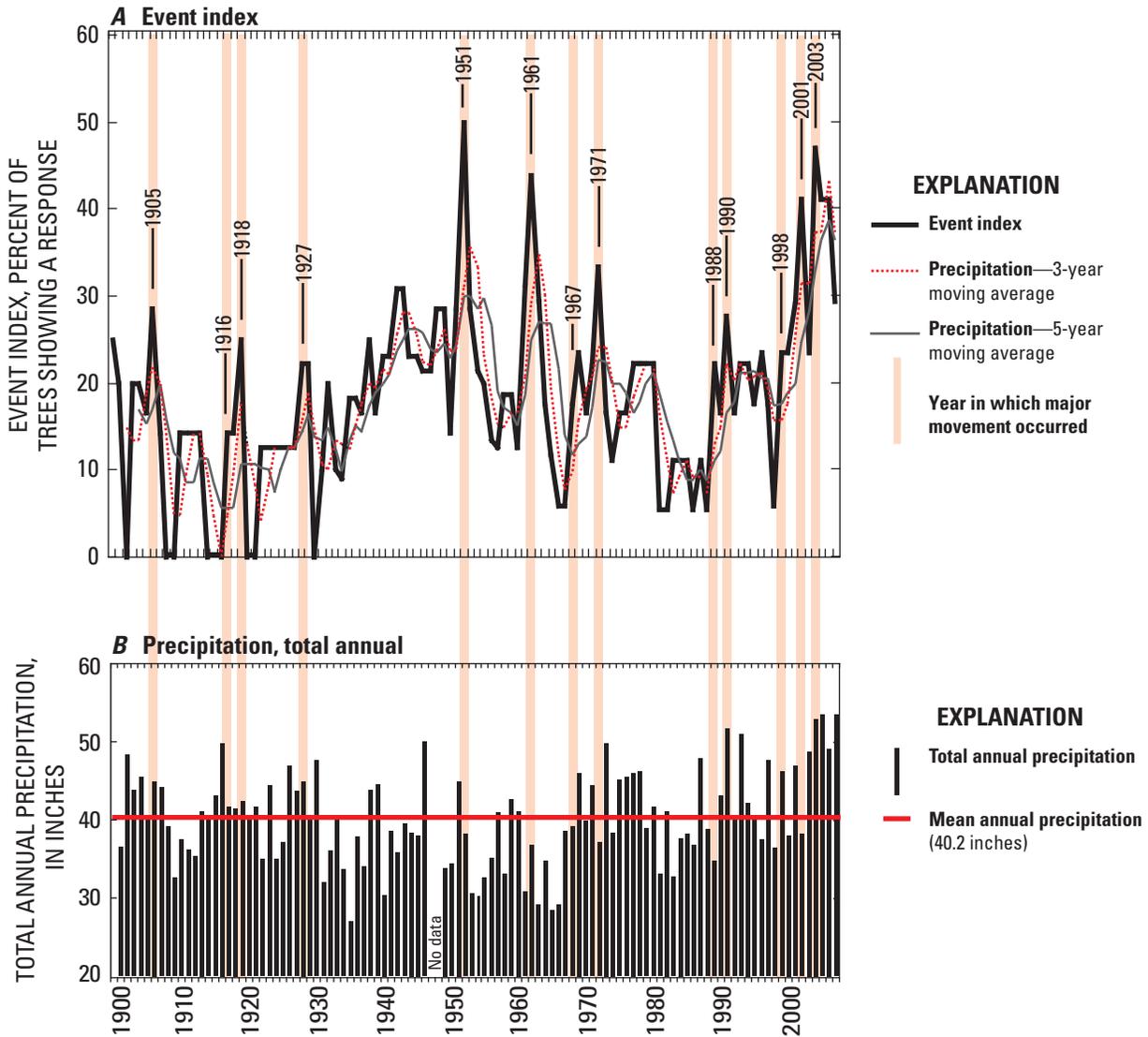


**Figure 5.** Event-response curve for Rattlesnake Gulf landslide, Onondaga County, New York: (A) Event-response curve, number of samples, and trend line, and (B) total annual precipitation and trend line for the period 1899 through 2007. (Location of rain gages shown in figure 1, inset map.)

indication of land movement) was lowest at the beginning of the analysis period. The 30-year period from 1899 through 1929 has 9 years with an event-index value of zero, whereas the 76-year period from 1930 through 2008 has an index value greater than zero every year. Individual years with a large spike in the event index, as opposed to a gradual change over several years, are considered years with substantial landslide movement (fig. 6A).

### Correlation with Short-Term Precipitation Patterns

A comparison of the 13 years with a sudden increase in event index (fig. 6A) with annual precipitation data (fig. 6B) indicates that 7 of these 13 years had above-average precipitation (1905, 1916, 1918, 1927, 1990, 1998, and 2003), but the analysis did not adequately relate the event index to the



**Figure 6.** Event-response index and annual precipitation data for the Rattlesnake Gulf landslide, Onondaga County, New York for the period 1899 through 2008: (A) Event index and years with substantial movement, and (B) total and average mean annual precipitation. (Location of rain gages is shown in fig. 1, inset map).

annual amount of precipitation, therefore a different approach was taken to determine if another precipitation period and the event index could be better correlated.

### Three- and Five-Year Moving Averages

A multiple linear regression equation was developed to reveal any correlation between the 3- or 5-year moving-average annual precipitation and event-index years. Results indicate that the 3- and 5-year moving averages were better correlated with the years of landslide movement than annual

precipitation (fig. 6A), but this analysis did not fully correlate the precipitation data to landslide events at this site.

### Dry Periods Followed by Wet Periods

Monthly precipitation prior to a substantial event response (landslide) was reviewed to determine if there was any correlation between periods of drought followed by above-normal precipitation as a possible cause for landslide movement. The monthly-precipitation assessment indicates that extended periods with below-average monthly

precipitation followed by a month or more with above-average precipitation might be a trigger for landslide movement. The process may begin with the formation of desiccation cracks, which commonly develop in silty-clay soils during dry periods, and can act as conduits through which precipitation readily flows downward to the poorly permeable, unweathered soil where it forms a water table that rises and saturates the overlying shallow, weathered soil. This saturation in turn decreases soil cohesion and allows thick masses of the loose, weathered soil to move downslope. This is consistent with a favored hypothesis for landslides in Tertiary sediments in New Zealand (McSaveny and Griffiths, 1987). Concurrent erosion of the landslide toe by high flows in the adjacent stream channel during relatively wet months may further destabilize the landslide material as hillside slumping propagates upslope. A comparison of wet periods that were preceded by a prolonged dry period in which a substantial event response occurred (fig. 6A) revealed that many, but not all, of the event years were consistent with this theory.

### Long-Term Patterns Related to Precipitation and Timber Harvesting

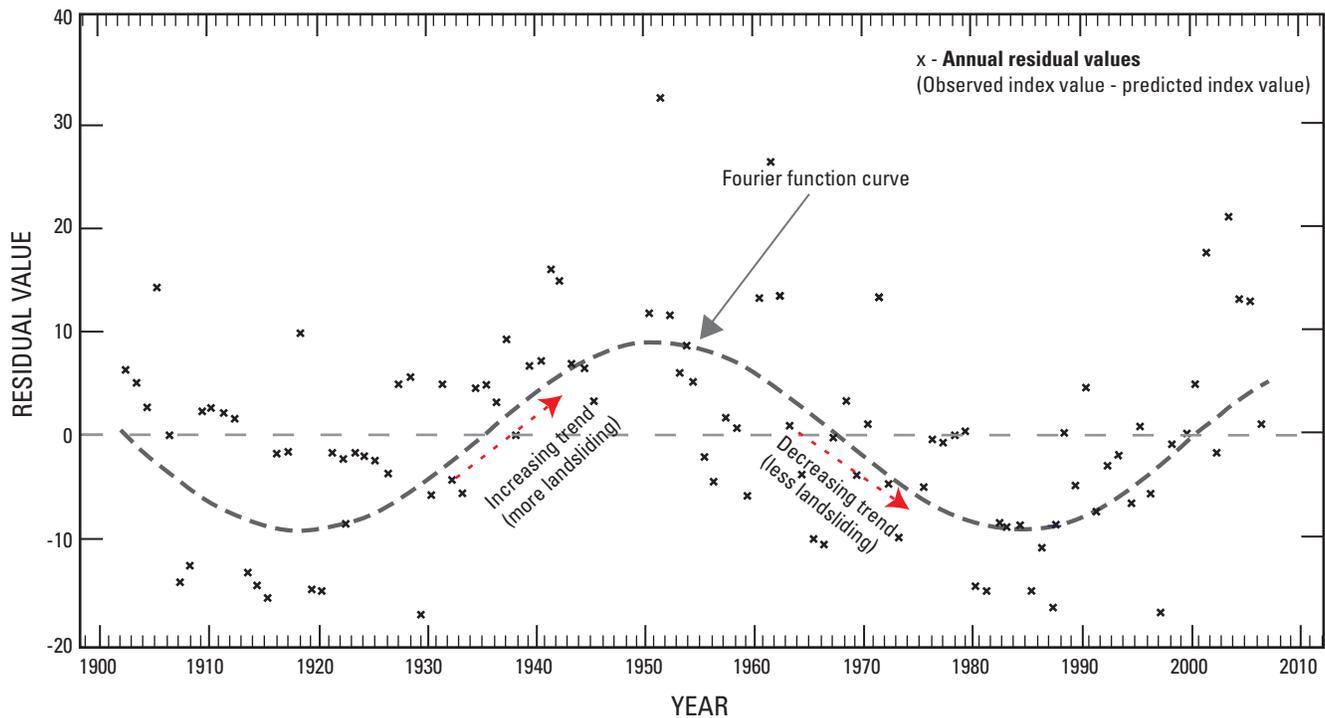
A residual-value analysis of the linear-regression results discussed above was done to identify any long-term pattern of landslide occurrence and to discern whether such a pattern

might also be related to long-term precipitation trends. The residual-value analysis entailed calculating the difference between observed event-index values and the index values predicted by the regression equation, then plotting the values (residuals) on a time scale through a periodic Fourier function<sup>2</sup> (fig. 7).

### Gradual Movement within Deep, Unweathered Soil

The residuals appear to indicate recurring decades-long cycles in landslide activity, wherein the frequency changes every 30 or so years (fig. 7). The residual values show an inflection point (change in slope) just before 1920, where the slope (representing landslide frequency) changes from downward to upward. The upward trend is consistent with slide occurrence recorded in the tree rings (see Event-Response Curve, fig. 5A). This trend peaks just after 1950, then declines until the mid-1980s, when it reverses and again continues upward through the present. This cyclic pattern may be indicative of movement within the deep, unweathered, clayey soil of the landslide—movement that probably results from the continuous erosion of the landslide toe by the

<sup>2</sup> In mathematics, a periodic function is a function that repeats its values after some specified time period. For example, the passages of the minute hand around a clock, or the phases of the moon, are periodic functions.



**Figure 7.** Residual-value analysis curve of event-index residuals for Rattlesnake Gulf in relation to a Fourier function curve for the period 1899 through 2006.

stream, as observed during several high flows during the study. This erosion of the toe results in an oversteepening of the slope, which in turn causes large blocks of soil to slump incrementally. The slumping slowly propagates uphill through the active landslide and possibly further upslope during the ensuing years and eventually results in a more stable slope configuration. Meanwhile, the shorter-term pattern of precipitation followed by shallow-soil movement above the unweathered layer continues.

## Deforestation and Timber Harvesting

An additional factor in the longer-term cyclic nature of landslide activity in Rattlesnake Gulf is deforestation, which has occurred in this area over the last 150 years and is considered to be a landslide trigger in the western United States and the Philippines (De la Fuente and others, 2002). Tree roots reinforce the soil, and the presence or absence of trees also affects groundwater levels, which in turn affect soil moisture and soil cohesion. Thus, the cutting of forests sharply decreases evapotranspiration and typically allows groundwater levels to rise until forest cover is re-established, while the gradual decay of roots destabilizes the hillside and further facilitates erosion of the soil and hillslope slumping.

About 80 percent of the original forests in central New York had been cleared for agriculture by the late 1800s (Singleton and others, 2001), but much of this region has undergone regrowth and reforestation over the past century; the oldest post-agriculture forests in central New York are about 75 years old (Singleton and others, 2001). The earliest aerial photographs of the Tully Valley (from 1937) show deforested areas upslope from several landslide areas, which

were smaller than the present Rattlesnake Gulf landslide. By 1951, the deforested area surrounding the Rattlesnake Gulf landslide had expanded, but then substantially decreased through reforestation by 1978. The present landowner reported that trees within the landslide area were selectively harvested in the mid-1990s. Tree harvesting in the early part of the 20th century may have affected landslide activity in Rattlesnake Gulf at that time, and the increase in landslide activity in 2000 may coincide with the selective harvesting that began when the forest again reached maturity in the 1990s.

## Summary

Dendrogeomorphologic study has provided a record of landslide activity that has occurred along Rattlesnake Gulf in the Tully Valley since 1899. Calculation of the event-response index (from trees whose rings indicate years of land movement) revealed 14 years during which landslide activity increased. Those years do not necessarily correspond to years with above-average precipitation, however, but the tree-ring data can be used to support the apparent correlation between years of increased landslide activity and months of extended drier than normal precipitation followed by months of greater than normal precipitation.

Slope stability is directly related to climate, soil composition and condition, and presence of forest cover. An event-response index curve, based on the tree-ring data, identified the years in which landslide frequency was greatest, and a multiple linear regression analysis of the results, followed by an analysis of the residual values

## Geotropism and Reaction Wood

*Tropism* is the orientation assumed by an organism through turning, curving, or differential growth in response to a stimulus. *Geotropism* is the response of a plant to gravity. Tree growth under normal conditions is vertical, against the pull of gravity, and produces nearly concentric rings around the center of a tree trunk. A change in a tree's angle from vertical, such as through persistent high wind, bending beneath the weight of a fallen tree, or soil erosion or earth movement at the roots, typically results in eccentric (asymmetrical) tree-ring growth and the production of reaction wood as extra ring thickness on one side of the tree trunk as it tries to regain vertical growth. Reaction wood is produced by the cambium, the thin layer of growing tissue around a tree, just inside the bark. Reaction wood in coniferous (evergreen) trees is termed "compression" wood and is found on the downward facing side of a tilted tree (fig. 4), whereas reaction wood in deciduous trees (those that lose their leaves each year) is called "tension" wood and is found on the upward facing side of a tilted tree (Aestello, 1971; Schroeder, 1980). Counting and measuring tree-ring widths reveals the date of tilting (Aestello, 1971).

through a Fourier function, indicates that landslide activity is loosely related to the 3- and 5-year moving-average annual precipitation and that a lag-time of several years may occur between a period of heavy precipitation and landslide movement above the unweathered-soil layer. Residual-value assessment of the event-response index also indicates that the Rattlesnake Gulf landslide activity is cyclic and possibly related to large-scale, long-term deep landslide movement that propagates uphill from the toe of the landslide at the stream into and beyond previously formed landslide-movement features. Shallow landslide activity may also result from desiccation cracks that form during periods of below-average precipitation and provide conduits through which subsequent precipitation can flow downward to the poorly permeable, unweathered layer and saturate the overlying shallow, weathered soil. Still another destabilizing factor for landslide soils could be the harvesting of trees above and within the landslide area; the removal of trees decreases evapotranspiration and thereby allows groundwater levels to rise during the growing season, which increases soil saturation above the weathered-soil layer. The concurrent decay of roots may facilitate further hillslope movement.

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