Smugglers Notch Slope Instability Report

Prepared for
Vermont Geological Survey,
Vermont Department of Forests, Parks and Recreation, and
Vermont Agency of Transportation
by

George Springston
Research Associate,
Department of Geology and Environmental Science
Norwich University
158 Harmon Drive
Northfield, VT 05663
(802) 485-2734
gsprings@norwich.edu

June 4, 2009

Disclaimer

On the cover: Cliffs on the west side of Smugglers Notch. Note extensive talus deposits at the base of the cliffs and debris flow scars. Photo by Tom Eliassen, Vermont Agency of Transportation.

Table of Contents

Figures

(continued on next page)

(continued on next page)

Tables

Plates

Executive Summary

Introduction
Concerns about the risks posed by the fall of a large boulder in Easy Gully on the west side of Smugglers Notch in the summer of 2006 led to this study of the overall slope instability hazards in the Notch. The end results are a delineation of the high landslide hazard areas within the Notch, determination of the months in which landslides are most frequent, and the documentation of the relationship between heavy rainfall and landslide events in the Notch.

Landslides, in the form of rock falls, rock slides, and debris flows have occurred in Smugglers Notch for thousands of years and we can expect large rock falls and slides and damaging debris flows to continue into the future.

Types of Landslides
Two types of slope failures or landslides occur in the Smugglers Notch area. The first broad class of landslides is the rock falls and rock slides, which involve one or many large pieces of rock detaching from a cliff and falling, bouncing, or sliding down a slope. Most of the boulders on the floor of the Notch appear to be the result of such rock falls. The second class of landslides includes the debris flows, which are slurries of water, mud, pebbles, cobbles, and boulders that flow within shifting channels on the talus slopes below the cliffs. In the Notch, they are caused by heavy rainstorms.

Size of Landslides
The rock falls can be expected to involve individual blocks well in excess of 500 or 1,000 tons. The largest block to fall since records have been kept appears to be the 11,500 ton (10,400 metric ton) piece that broke off the west face north of Easy Gully on July 17, 1983.

The debris flows can be expected to range from a few cubic meters of mud, pebbles, cobbles, and boulders up to many thousands of cubic meters. The largest recorded debris flow descended from the east side on May 13, 1986 and consisted of about 327,000 cubic yards (250,000 cubic meters) of material. This blocked Vt. Route 108 and the West Branch at the site of the pull-off near the Cambridge-Stowe line. Future debris flows can also be expected to sweep down to and across Vt. Rt. 108.

Eyewitness Reports
Only two eyewitness reports of landslides in Smugglers Notch are known. One involved a rock fall event and the other involved debris flows. In both cases, the witnesses fortunately escaped unharmed.

The first account is that of Mr. Dan Rogers of Jeffersonville, who witnessed the rock fall event of July 13, 1983 (see Table 7.1). According to the account in the Morrisville, Vermont News and Citizen for July 28, 1983, Mr. Rogers was running up Rt. 108 when he heard a “sonic boom.” About 60 seconds later, boulders came crashing down through the trees ahead of him. He then saw boulders rolling out across the road (Baskerville and others, 1988, p. 6).

The second account involves the May 22, 1986 debris flows (see Table 7.1). Lee and others (1994) report that Mr. Brian O'Toole of Cambridge was driving southward through the Notch during heavy rainstorms late on the night of the 22nd. Travel became difficult as he tried to descend from the height of land and he finally had to abandon his car due to mud and gravel deposits coming across the road. As he struggled southward on foot he apparently walked through or around these flows. The West Branch was out of its banks in places and travel was very difficult. He eventually was picked up by a State Police car somewhere south of Big Spring.

Months of Occurrence

Of 21 landslide events at Smugglers Notch and Mount Mansfield for which the month of occurrence can be determined, all occurred between May and December, with 19 of them occurring between May and October. The peak monthly occurrence is in July. Maintenance records from the Vermont Agency of Transportation suggest that there is also landslide activity that occurs prior to the opening of the road in May. This is most probably related to the spring thaw.

Precipitation as a Trigger

The history of landslides in the Mount Mansfield area, in the White Mountains of New Hampshire, and in many other regions shows a strong correlation between intense precipitation (and/or rapid snowmelt) and landslides. This correlation can be used to give some warning of times with an increased likelihood of landslide activity at the Notch. In a study of debris avalanche activity in the White Mountains of New Hampshire, Milender (2004) proposes a two-part threshold:

1. Storm delivering 2 inches in 24 hours with peak intensity of 0.7 inches/hour or greater.

2. Storm delivering 2.5 inches or more over 30 hours.

The first threshold is for a very intense storm of short duration, while the second is for cases of storms of longer duration that are not as intense. Although climatic and geologic conditions are not identical to the White Mountains, these thresholds appear to be reasonable starting points for predicting times of debris flow hazard in the Smugglers Notch area. These thresholds are also broadly consistent with the observations of Mr. Edward Salvas of WCAX-TV on triggering levels that are cited on page 62 of this report (3 inches or more).

Landform Map

The landform map shows the areas of historic landslide activity. These landforms are largely the result of slope degradation processes. Weathering weakens exposed rock on the outer faces of the cliffs and in the rock chutes. Thus, rock fall can occur from any location on the cliffs. This process has in the past built up the large talus deposits and is still quite active today. Debris flows, by contrast, appear to originate below rock chutes which serve as source areas for rock debris and serve to focus stormwater and/or rapid snowmelt from catchments on and above the cliffs. Some of these debris flows may actually start out as debris slides, but by the time they reach the lower parts of the talus slopes and debris cones, the landforms and deposits indicate that they are rapidly moving slurries of debris.

The large boulders that litter the floor of the Notch are strong evidence that rock fall hazards are high. Although the well-developed soil and vegetation on some indicate that they fell long ago, there is abundant evidence (as outlined in Chapter 7) that they continue to come down today.

The level of debris flow activity appears to be accentuated on the west side of the Notch due to the increased height of the mountain slopes and the concave topography on that side, a combination that results in enlarged catchments for the rock chutes. By contrast, the east side of the Notch is lower and much of the east side has a convex topography, resulting in smaller catchments. Note, however, that the largest recorded debris flow event occurred on the eastern side at the southernmost debris flow near the Stowe-Cambridge town line. This is not surprising as this feature has one of the larger catchments in the study area.

Slope Instability Hazard Map

The slope instability hazard map shows a relative ranking of areas of high and moderate hazard on the basis of evidence for continued and future rock fall and debris flow hazard. In addition, two areas of high fluvial erosion hazard (active alluvial fans) are shown. This map is based on a combination of historical evidence, earlier geologic studies, interviews with knowledgeable persons, field work, and aerial photo interpretation.

Recommendations

The recommendations fall into two categories, management and monitoring. As documented in this report, there is sufficient information available to identify the high landslide hazard areas within the Notch. The months in which landslides are most frequent are reasonably well constrained. The relationship between heavy rainfall and landslide events in the Notch is well-established. However, in order to undertake effective management of the risk posed by landslides to the public, additional information is still needed.

Highway signs need to be moved down

The "Watch For Fallen Rocks" signs need to be moved down to the Cambridge/Stowe town line for traffic coming from the south and at least 1,500 feet north of the main parking lot for traffic coming from the north. Additional signs at the main parking lot and at Big Spring would be helpful, but these would be well within the higher hazard parts of the Notch.

Warning signs

Warning signs should be placed and maintained at trailheads and other access points for foot travelers.

Parking areas need to be reorganized

The informal parking area at the base of the Hidden Gully debris flow outlet should be closed off. This debris flow path seems to be particularly active and can be expected to disgorge large quantities of mud, pebbles, cobbles, and boulders during or after large rain events. At most this should be left as a spot where a single car can pull over to let others pass.

The areas of widened shoulder opposite the site of the October 21, 2007 rock slide (several hundred feet north of the main parking lot) should be rearranged to discourage parking of vehicles. Future slope failures are very likely in this vicinity.

Discourage any rogue camping at parking spots

I have not observed any camping taking place at the parking spots but, given the level of day use, at least occasional overnight tenting may be occurring. Campers sleeping in vehicles or tents at the pull-offs would be particularly vulnerable to rock fall or debris flow events occurring in the midst of a heavy rain storm.

Issue warnings based on real-time rain gage or weather radar

A recording rain gage with real-time telemetry should be established as close to the Notch as feasible. This should be located at a site with electric power so that it can function properly during times of snow and ice that occur even in the warmer months. Telemetry can be via land line, cell phone, radio, or satellite. One possibility would be to work with the USGS, who already has stream gaging stations on the West Branch of the Little River and Ranch Brook. USGS currently runs a rain gage at the West Branch site, but it is not connected via telemetry. Alternatively, an arrangement could be made with one of the two ski areas.

As outlined in this report, we have a good idea of the amount of precipitation that is required to trigger slope failures. When precipitation amounts and/or rates exceed the threshold values described in this report, emergency personnel could be alerted and warnings could then be issued regarding slope failures. A cooperative arrangement involving the National Weather Service and other organizations such as the Vermont Emergency Management Agency and the VAOT is probably the most effective way to disseminate the resulting warnings.

Alternatively, the National Weather Service is developing a computer system to perform rapid flash flood hazard warnings. The system, called Flash Flood Monitoring and Prediction (FFMP), combines radar information on precipitation intensity with accurate maps of small drainage basins and estimates of the amount of rainfall needed to produce flash flooding. The system is described on the National Weather Service website (http://www.nws.noaa.gov/mdl/ffmp/.) If applicable to the Smugglers Notch terrain and climate, this could be of great utility.

Near-real-time warnings based on precipitation, such as those described in the preceding three paragraphs, are likely to be the most effective actions that can be taken to reduce risk to the public from landslides at the Notch.

Include the Notch in statewide earthquake preparedness

Rainfall is not the only possible trigger for landslides in the Notch. As is well known, landslides can be triggered by earthquakes of sufficient magnitude. Thus, emergency planners should recognize that the possibility of rock falls in the Notch would be increased immediately following a substantial earthquake. This could result in a temporary closure of Vt. Rt. 108, thus blocking movement of vehicles between Stowe and Cambridge.

Continue landslide monitoring in the Notch

Monitoring of debris flow and rock fall/slide activity at the Notch should be continued. Information on the location, date, time, type of landslide, source area, volume of material, damage, and antecedent weather conditions should be recorded for each event. Observations during this study indicate that the debris flows cannot be expected to continue in their exact present locations; the debris flow paths are liable to shift over time as blockages occur.

For tracking of changes in the cliffs and talus slopes over time, it will also be important to build up a set of high-resolution images of the cliffs, taken from known stations. The photos should be taken in the spring prior to leaf-out but after snowmelt is largely completed (typically early May) and in the fall after the leaves are off the trees (October or early November.) Suggested locations for repeat photography are listed in Table 7.3.

1. Introduction

> *Between Mansfield and Sterling Mountains a deep gorge intervenes, known as "Smuggler's Notch," through which in the early settlement of that part of the State a "bridle road" was kept open, and tradition says contraband goods were secreted in and found their way through it; but latterly no one disturbs its solitude, except it be a hunter or one seeking an exhibition of nature in her wildest and most romantic haunts. To the latter there is here opened a rich field—for even the far-famed "Franconia Notch" presents no wilder views or towering precipices, than are found in this sequestered glen.*
>
> Hitchcock and others, 1861, Geology of Vermont, p. 879-880.

Smugglers Notch is a narrow mountain pass located in the Towns of Cambridge and Stowe in Lamoille County, Vermont (Figure 1.1.) It is flanked by Mount Mansfield on the west and Spruce Peak on the east and is largely within the Mount Mansfield State Forest. Vermont Route 108 winds through the narrow floor of the Notch, which is studded with large talus blocks and overhung by tall cliffs. This section of Route 108 has been designated as the Smugglers Notch Scenic Highway, one of the two State Scenic Highways in Vermont (Lamoille County Regional Planning Commission, 1995.)

Smugglers Notch is home to an uncommon assemblage of plants and animals. Natural communities present in the Notch include Montane Spruce-Fir Forest, Red Spruce-Northern Hardwood Forest, and Boreal Calcareous Cliff (Lamoille County Regional Planning Commission, 1995; Thompson and Sorenson, 2005.) Numerous rare plant species are found among the cliffs and on the slides, with several of the arctic plant species being near their southern range limits. The cliffs also provide an important breeding site for peregrine falcons.

Widely known as a scenic landmark, the Notch is visited by thousands of people every year. The Vermont Agency of Transportation lists the 2008 average annual daily traffic volume as 1500 vehicles per day (Traffic Research Unit, 2009.) The mountains and cliffs draw hikers, rock climbers, and ice climbers throughout the year. One indication of the off-road level of public use is given by statistics from the hiker sign-in boxes on some of the trails. Useage for 2001 was as follows: Hell Brook Trail 1,827; Elephant's Head Trail 1,030; and Sterling Pond Trail 13,256 (Vermont Department of Forests, Parks, and Recreation, 2002, Appendix C.)

2. Previous Work

An excellent summary of the history of travel and tourism in Smugglers Notch and the Mount Mansfield area is contained in Hagerman (1975.) This work also includes a history of landslides in the area, which was the starting point for the table of landslides in Chapter 7.

Jacobs (1938) gave a general description of the bedrock geology of the area and speculated on the processes that had shaped the Notch.

A general description of the geology of the Mount Mansfield State Forest is given in Christman (1956.) This booklet contains preliminary results from the author’s 1959 publication. Besides descriptions of the rocks and structures, it contains sections on the evidence for glaciation and on the origin of the Notch.

The first detailed account of the bedrock geology of the Notch is given as part of the study of the bedrock geology of the Mount Mansfield 15-minute quadrangle by Christman (1959.)

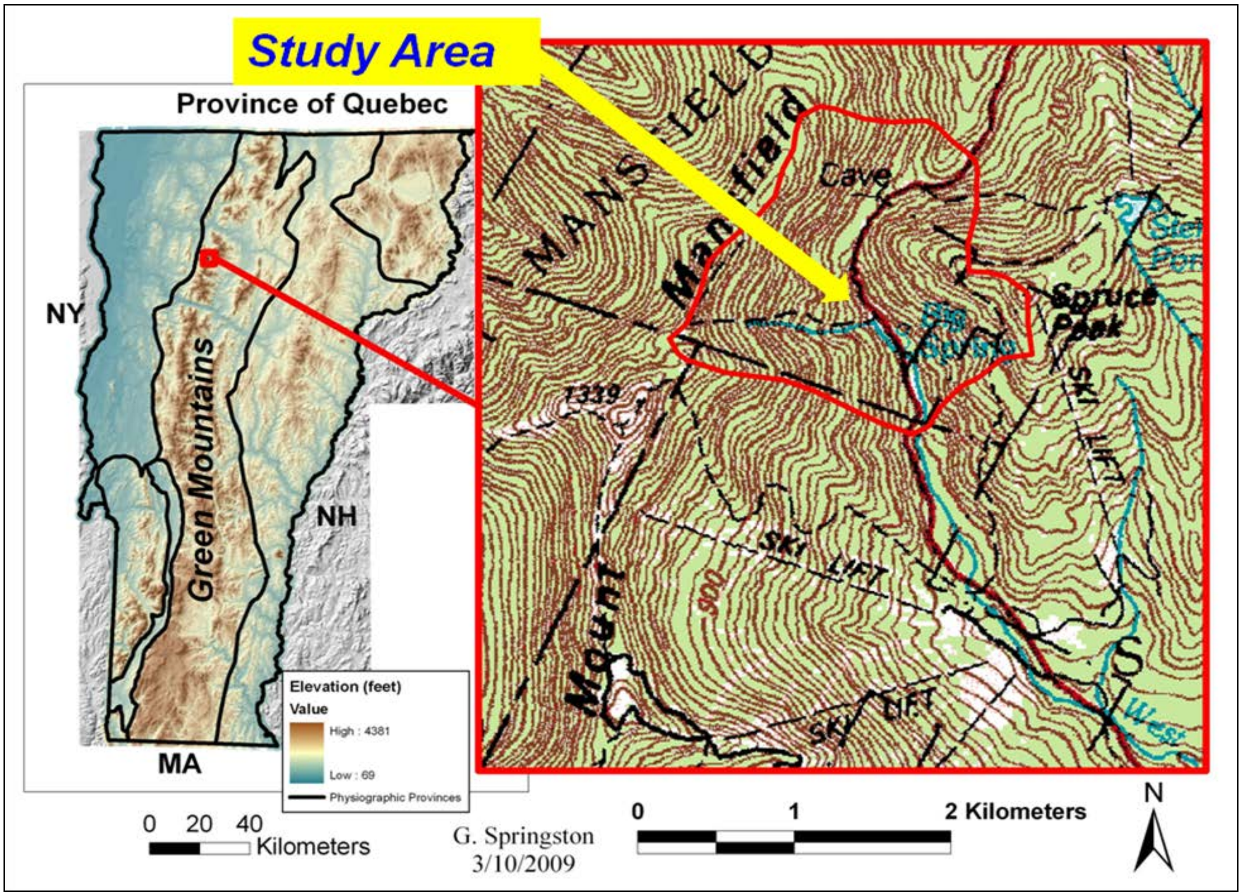


Figure 1.1. Study area location.

Stewart (1961) briefly discusses the origin of the Notch and, in addition to recognizing the importance of stream erosion and glacial scouring, pointed out the importance of weathering and talus accumulation in the geologic development of the Notch.

In the 1980s, then State Geologist Charles Ratté worked with the U.S. Geological Survey (USGS) to initiate a set of studies of landslide hazards in Vermont. Due in part to large rock fall and debris flow events in the 1980s, part of this work focused on Smugglers Notch. The results are summarized in a series of publications, including Baskerville and others (1988), Lee and others (1994), and Lee and others (1997.) The USGS updated and expanded Hagerman’s (1975) list of landslide events. This work also included documentation of rock falls and debris flows, field mapping of the bedrock fracture systems, aerial photo analysis of lineaments, and monitoring of temperature and displacement of joint blocks at two sites in the Notch over a 13 month period (Lee and others, 1997.) The USGS studies were also the subject of a Vermont Geological Society field trip in 1991 (Baskerville, 1991.)

The Smugglers Notch Scenic Highway Corridor Management Plan (Lamoille County Regional Planning Commission, 1995) includes extensive discussions of the natural resources in the Notch, including a section on the geology of the Notch. In the subsection on "rockfalls and slides", the report concludes that "Monitoring of sensitive geological areas could be of benefit to inform the VAOT and others responsible for coordination of road closure strategies when weather and other climate influences increase rockfall potential and thus would have the potential to reduce risk to the public." And later "…it should be priority in the planning of recreational facilities that unstable areas on the rock slides and cliff bases be avoided as much as possible" (p.16.) The recommendations in this section of the corridor plan are still relevant to the issue of landslide hazards in the Notch and are therefore included below:

> *Promote education regarding geological instability to public agencies, adjacent communities and visitors to the Notch.*
>
> *Implement a monitoring program of unstable rock faces and coordinate with VAOT, ANR/DFPR and the Local towns.*
>
> *Develop a road closure strategy for implementation during high risk times.*
>
> *Formalize an ongoing study with the USGS to evaluate geological stability.*
>
> *Incorporate design approaches that avoid high risk areas for trails and other public facilities.*
>
> (Lamoille County Regional Planning Commission, 1995, p. 16)

Detailed bedrock geologic mapping in the Mount Mansfield 7.5-minute quadrangle was undertaken in the 1990s by Peter and Thelma Thompson (Thompson and Thompson, 1998.)

Bierman and others (1999) discussed the rock fall and debris flow events at Smugglers Notch and visited two sites in the present study area; the debris flow site at the Stowe-Cambridge town line and the main parking area in the Notch.

As part of a statewide highway rockfall hazard study, Eliassen and Springston (2007) conducted an evaluation of Vermont Route 108 in Smugglers Notch. This study used a modification of the rating system of Pierson and others (1993.) The resulting score was the second highest of the 150 high-hazard rock cuts in the State, ranking only behind a section of Vermont Route 5A in Westmore.

Relevant studies in the White Mountains of New Hampshire include the debris avalanche studies of Flaccus, 1958 and 1959; Kull and Magilligan, 1994; and Milender, 2004 as well as the rock stability studies of the Old Man of the Mountains, summarized in Fowler (2005) .

3. Study Methods

Research consisted of a combination of literature review, archive research, aerial photo interpretation, field photography, field mapping of landscape features and surficial geologic materials, and detailed mapping of bedrock features along the bases of the cliffs and up the rock gullies as far as feasible. A climb partway up Easy Gully was made with the assistance of the Stowe Mountain Rescue Service. Areas of the cliffs that could not be visited in person were viewed by telescope and photography from the opposite side and from low-level aerial photos. Field studies were undertaken from July of 2006 into November of 2007.

A detailed photogrammetric study of the Notch was contracted out to James W. Sewall Company, of Old Town, Maine, with geodetic control survey work supplied by the Geodetic Section of the Vermont Agency of Transportation. Products included a set of 1:12,000 natural color aerial photo prints, a set of natural color orthophotos with 1 foot pixel resolution and a topographic map at 1 inch = 100 feet with 2 meter contours. These were very helpful in performing the detailed field work. Stereoscopic examination of the aerial photos was used to identify many of the subtle terrain features. The orthophoto serves as the base map for Plates 2, 4, and 5 and the topographic map is incorporated into Plate 1.

Older aerial photos (May, 1962) were also examined stereoscopically. These were exceptionally sharp and free of shadows and helped in delineating features on the east side of the Notch. A partially georectified version of one of the 1962 photos is shown in Plate 3. Since this is not an orthophoto, some distortion remains and measurements cannot be made as accurately as on Plates 2, 4, and 5. It does, however, provide our best view of the talus slopes and cliffs on the east side of the Notch.

Many sources were consulted for the historical information, most of which is presented in Chapter 7 of this report. Robert Hagerman's *Mansfield: The Story of Vermont's Loftiest Mountain* (Hagerman (1975) served as a great starting point. Libraries and Archives were searched, including the Kreitzberg Library at Norwich University, The Bailey Howe Library and Special Collections at the University of Vermont, the Kellogg Hubbard Library in Montpelier, the Stowe Free Library, the Stowe Historical Society, the Vermont State Library in Montpelier, the Vermont Archives in Montpelier, and the Vermont Historical Society in Barre. The online photo collection of the Vermont Landscape Change Program was reviewed. As part of this work newspaper indexes were checked for references to slope failures in and near the Notch. Partial indexes were available for the Burlington Free Press and a search was made of the New York Times online index and the *Early American Newspapers* online database.

4. Physiography and Geology

Occasional glimpses of the sterile peaks of Mansfield are caught from the road leading up to the spring, and, as the latter spot is approached, the precipitous-walled sides of Mansfield and Sterling Mountains crowd more closely upon each other, and are not more than twenty rods apart. Bowlders of gigantic size lie scattered in the gorge near the spring and are quite numerous north of it; but in the southern portion they are only rarely seen.

Hitchcock and others, 1861, Geology of Vermont, p. 880.

The first part of this chapter describes the general physical features of Smugglers Notch. The second part describes the bedrock geology and the final part gives an overview of the processes that have shaped the Notch. Note that the results of the detailed mapping of landforms will be presented in later sections.

Physiography

The topography of Smugglers Notch is shown generally in the right-hand portion of Figure 1.1 and in more detail in Figure 4.1. The amphitheatre of steep cliffs on the west side is clearly shown. Note that in map view this wall of cliffs is concave toward the center of the valley. By contrast, the cliffs on the east side are convex toward the center of the valley. Figure 4.2 shows a topographic profile from Point A to Point A' in Figure 4.1. The floor of the Notch is at an elevation of 2,160 feet (658 meters.) Note that the west side is substantially higher than the east side. The mountain slopes on the west side extend up to over 4,120 feet (1,255 meters) while those on the east side extend up to 3,120 feet (950 meters.) The individual cliff faces on the west side are higher than those on the east, with those on the west side up to about 525 feet high (160 meters) while those on the east side are not more than about 330 feet (100 meters.) These differences in convexity and in height are significant in evaluating the landslide hazards and will be discussed later in this report.

The extent of the cliffs on both sides of the Notch is shown in Figure 4.3. Figure 4.4 shows the rock fall sources that can be dated and the distribution of fallen boulders in the floor of the Notch. The known landslide events (rock falls and debris flows) are described in detail in Chapter 7. See especially Table 7.1.

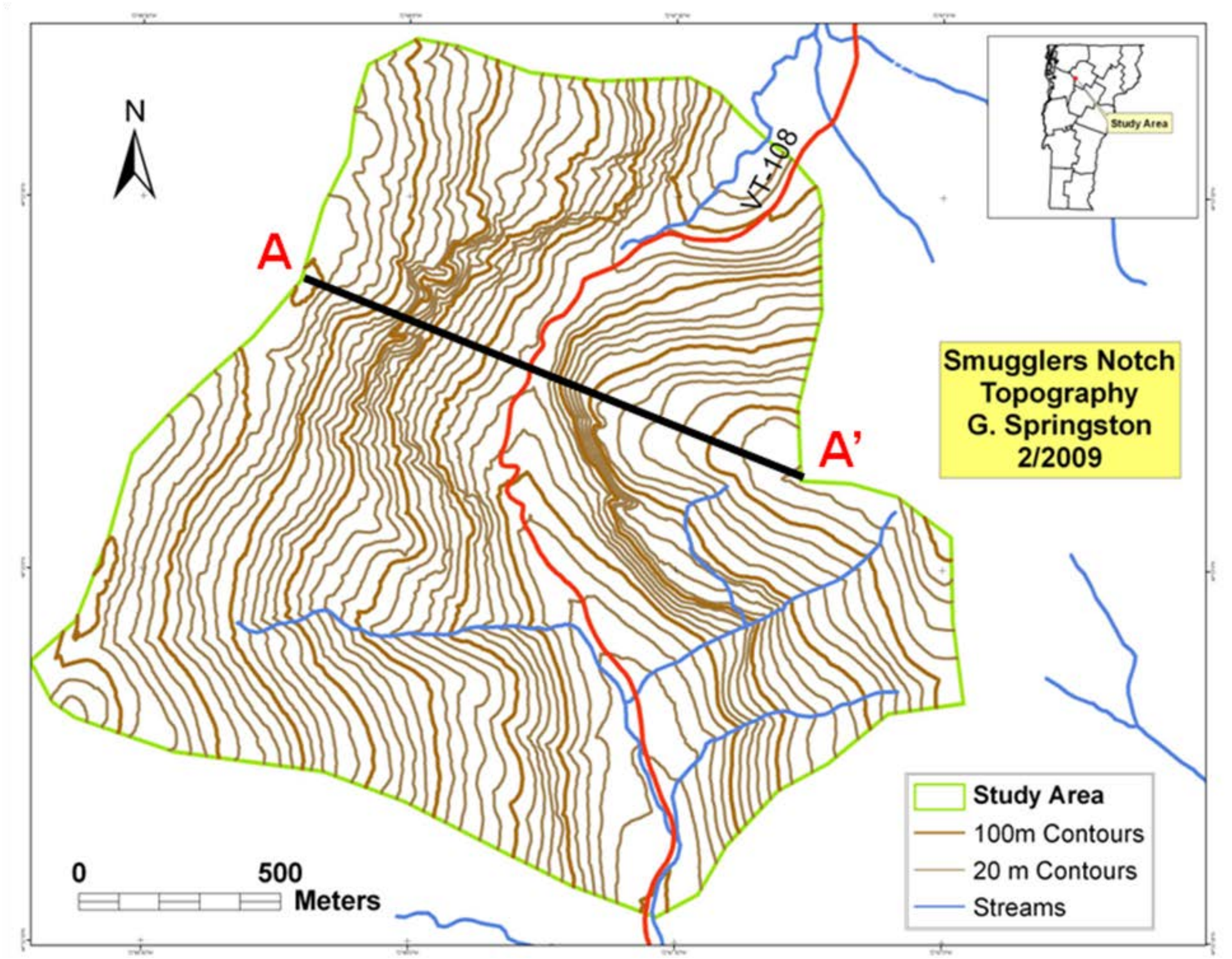


Figure 4.1. Topographic map of the Notch. The contours are derived from the photogrammetric mapping undertaken as part of this study. The contour interval is 20 meters. Compare the concave-outward amphitheatre of steep cliffs on the west side of the notch with the convex-outward promontory that makes up the eastern side.

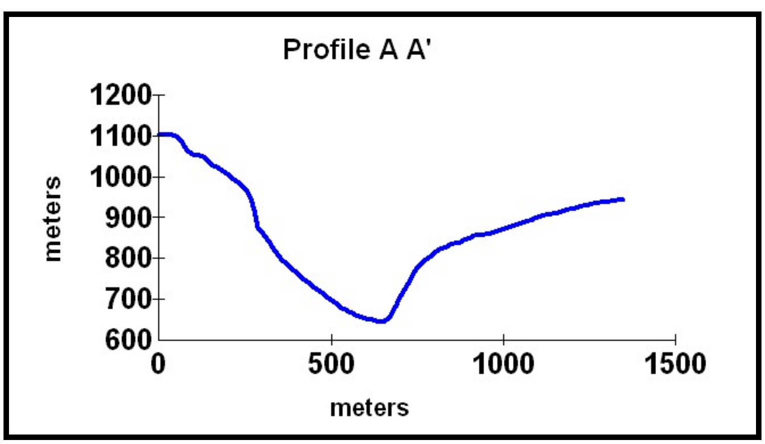


Figure 4.2. Topographic profile A-A' across the Notch. See Figure 4.1 for location. Note that the west side is substantially higher than the east side.

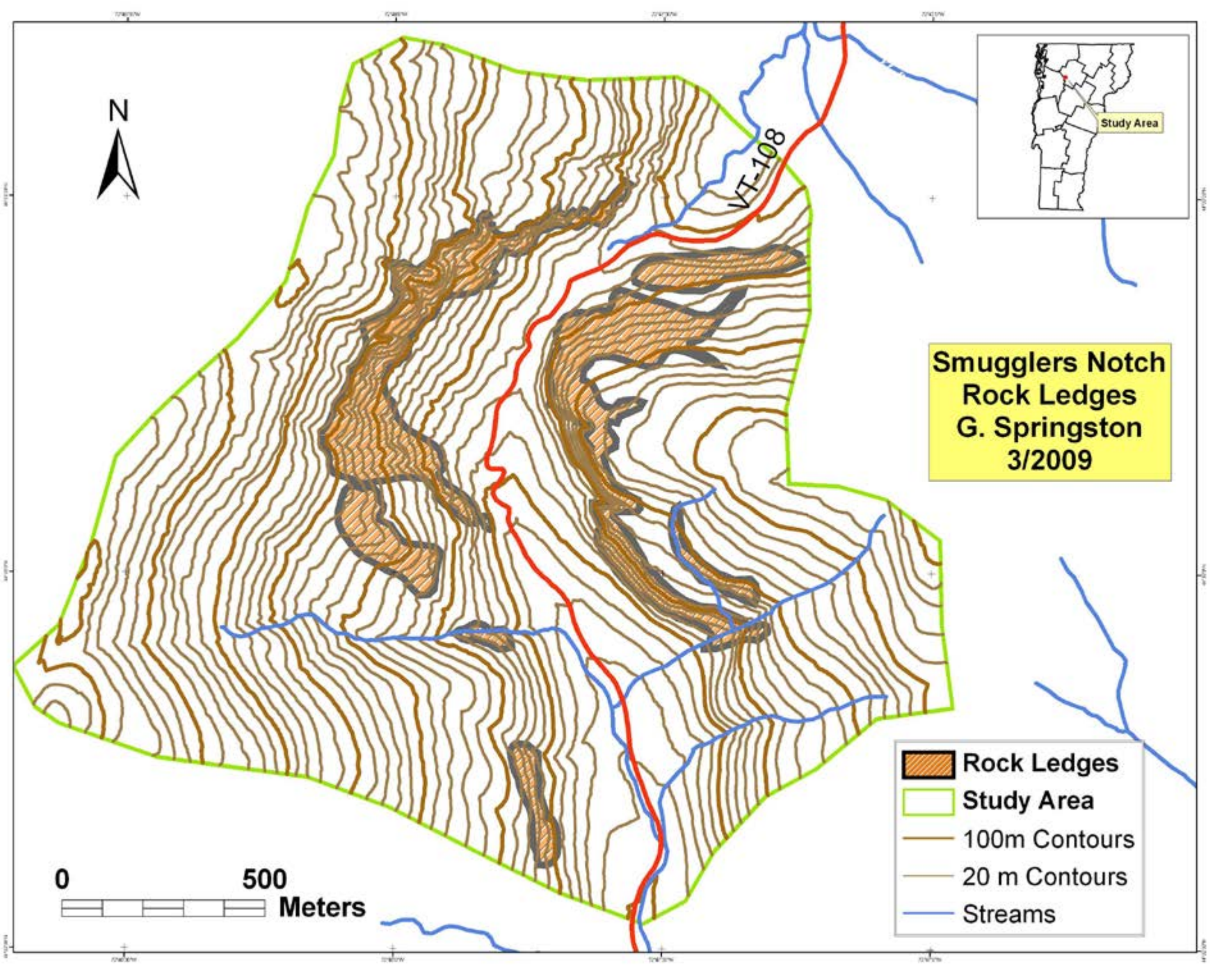


Figure 4.3. Rock ledges at Smugglers Notch. Derived from a combination of photogrammetry, stereoscopic aerial photo interpretation, and field mapping. Scattered ledges of smaller size are not shown. These are abundant on the mountain slopes above the ledges shown on this figure.

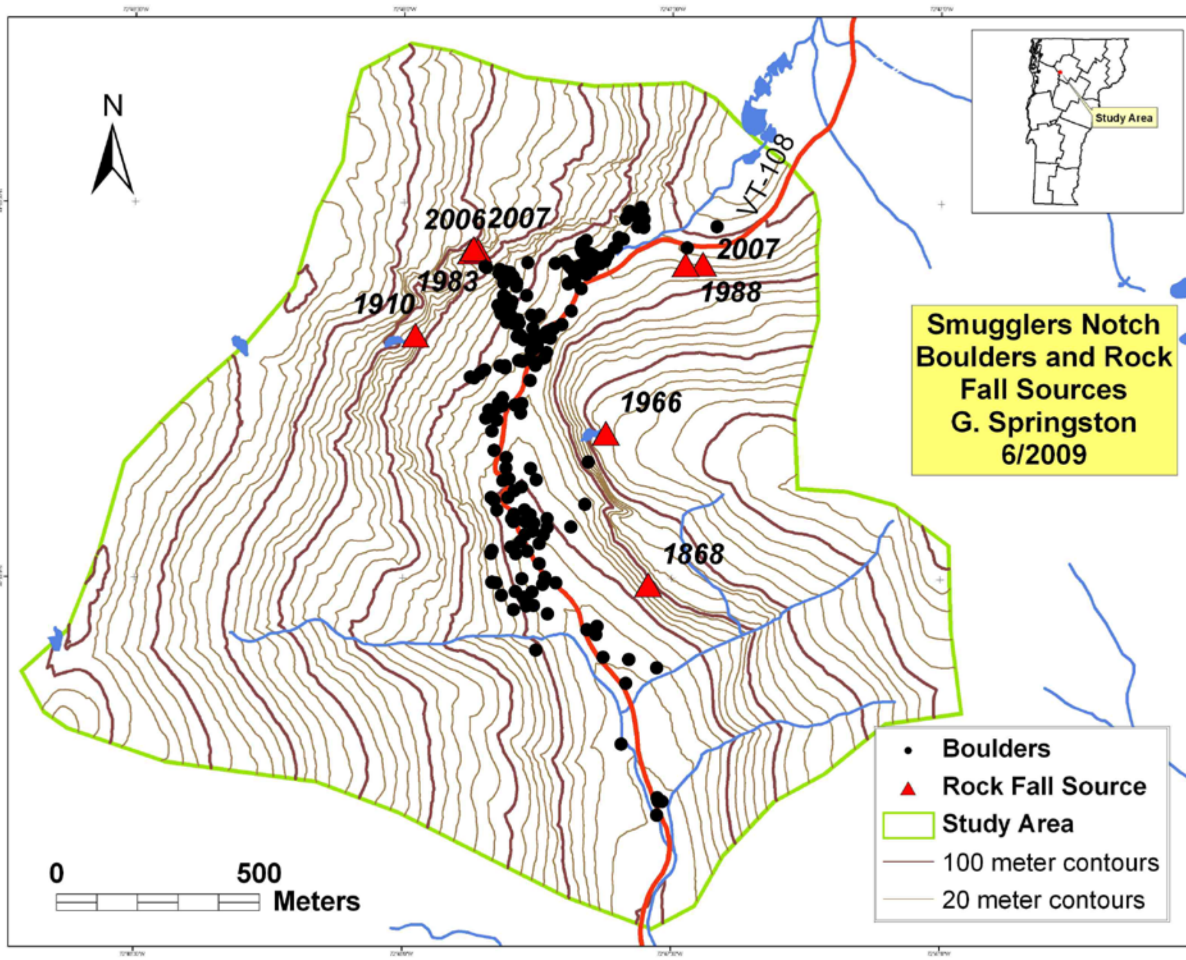


Figure 4.4. Documented rock fall sources and fallen boulders at Smugglers Notch. Only rock fall sources with definite dates are shown. There are many additional locations on the cliffs where blocks have clearly become detached in recent times. The boulders shown on this map are those located during the photogrammetric mapping, by stereoscopic aerial photo interpretation, and during field mapping.

Looking northeastward from The Nose on Mount Mansfield, Figure 4.5 clearly shows the rugged character of the Notch. Rocky cliffs rise abruptly several hundred feet above a valley bottom of talus. This view shows the northern "arm" of the Notch, which trends northeasterly from near the height of land in the Notch.

The extensive amphitheatre of cliffs that makes up the west side of the Notch is clearly evident in the aerial view shown in Figure 4.6. The apron of talus at the base of the cliffs is accentuated by the thin snow cover and is cut by rockslide tracks and debris flow channels. The prominent cone of debris flow materials below Easy Gully is visible to the right of center at the bottom of the frame.

Figure 4.5. The Notch as seen looking north from Mount Mansfield, from north of The Nose.

Figure 4.6. Aerial view of the west cliffs showing talus apron and debris flow tracks. Figure 4.10 shows the left (southern) portion in greater detail. Photograph taken on November 9, 2007 by Tom Eliassen, Vermont Agency of Transportation.

Another view of the western cliffs is shown in Figure 4.7. Starting at the left of the photo, the long rock chutes south of Cass's Gully are visible, then the inverted "V" of whitish rock slide and debris flow paths at the base of Cass's Gully, the high, dark cleft of Hidden Gully, and the broad whitish scar at the base of Easy Gully.

Figure 4.7. Aerial view of west cliffs. From left to right: Cass's Gully, Hidden Gully, Easy Gully (with prominent slide scar) and cliffs above main parking lot. Photograph taken in November, 2006 by Tom Eliassen, Vermont Agency of Transportation.

A closer view of the Cass's Gully and Hidden Gully sections of the cliffs is shown in Figure 4.8, taken from the base of Elephant's Head Gully. The cliffs on the right side of Cass's Gully were the origin of the great boulder known as King Rock, which fell about 1910. See the photos in Chapter 7 and Table 7.1.

As shown in Figure 4.9, from Cass's Gully southward a prominent feature is the set of long rock chutes that extend well up above the main cliffs, almost to the ridgeline. These appear to feed water and rock to the debris flow tracks on the talus deposits below the cliff. Note that the debris flow channels extend down to the "S" turns in Vermont Route 108. As described in the historical section, debris flows are active in these channels during and immediately following heavy rainstorms.

Figure 4.8. Cass's Gully and Hidden Gully sections of west cliffs. Photo from Elephant's Head Gully on September 15, 2006. Photo courtesy of Marc Couper, Stowe Mountain Rescue Service.

An aerial view of the northern parts of the cliffs and talus on the west side is shown in Figure 4.10. The Easy Gully scar is prominent to the right of center. Note the large blocks of talus adjacent to the parking lot at the bottom of the photo. Although in all likelihood rockfall activity off of the cliffs above the parking lot is high, only one report of rocks reaching the parking lot in historical time has been found. This involves some sort of rock fall from the northwest cliffs or Easy Gully that damaged or destroyed the roof of the information booth in 1973 (see Table 7.1 and Lamoille County Regional Planning Commission, 1995.) It may be that the large blocks that have fallen in the past have to a great extent shielded the parking lot from direct rock falls from moderate-sized blocks.

Figure 4.9. Aerial view of the western cliffs and debris flow tracks south of Cass's Gully. Note that the rock chutes that feed some of the tracks extend up above the main cliffs almost up to the ridgeline. Photograph taken on November 9, 2007 by Tom Eliassen, Vermont Agency of Transportation.

Figure 4.10. Aerial view of west cliffs from Cass's Gully north. Shadows accentuate the major gullies or rock chutes on the cliffs. Note main parking area with cars at bottom. Photograph taken in November, 2006 by Tom Eliassen, Vermont Agency of Transportation.

The cliffs of the eastern side of the Notch are shown in Figure 4.11, which was taken from The Nose. At left are the broken cliffs southeast of the parking area. In the center is the dark gash of the Elephants Head Gully and the Head itself to the right of the Gully. High cliffs continue to the right edge of the frame. As on the west side, note the apron of talus at the base of the high cliffs. Field work and aerial photo interpretation indicate that debris flow activity is more limited on the east side than on the west, although a large cone of debris flow material emanates from the Elephants Head Gully area. Although debris flows may be more limited on the east side, the largest single debris flow event at the Notch came down from the eastern cliffs on May 22, 1986, blocking Rt. 108 and the West Branch of the Little River near the Stowe-Cambridge town line. This was part of a set of 12 or more events that occurred following heavy rains. See Chapter 7 and Table 7.1.

Figure 4.11. The Elephant's Head buttress and the eastern cliffs as viewed from Mount Mansfield, north of The Nose, April 26, 2007.

Figure 4.12 is another view of the Elephants Head area, showing the eastern talus apron, which is prominently studded with large talus blocks.

Figure 4.12. Elephant's Head buttress to left of center with talus apron below. January 20, 2006. Photo courtesy of Marc Couper, Stowe Mountain Rescue Service.

Figure 4.13 shows the northern parts of the eastern cliffs, above and south of the main parking lot. This was taken from Easy Gully at the base of the cliffs. Note the prominent rock chutes trending down and to the left. These, like chutes throughout the Notch, are formed by erosion along fractures in the bedrock. The chutes shown in the figure appear to concentrate together any rocks falling from the cliffs above them. Tim Wilson of the Agency of Transportation reports that a boulder originating on the north part of these cliffs reached the road south of the main parking lot (personal communication, January, 2008.) The rock chutes in the foreground also serve to concentrate snow avalanches.

General Geology

Smugglers Notch is located in the Green Mountain physiographic province of Stewart and MacClintock (1970.) The study area is underlain by late Proterozoic to Cambrian schists that have been metamorphosed to garnet grade. Figure 4.14 shows the bedrock units as mapped by Thompson and Thompson (1999.)

Only two lithologies were encountered on the cliffs of the Notch. The predominant unit on the cliffs is rusty-weathering, graphitic, quartz-muscovite-chlorite-albite schist. The albite in this unit is commonly dark gray to black. It appears that this unit makes up most of the upper portions of the cliffs on both sides. The lower portions of the cliffs consist of silver-green to gray-weathering chlorite-quartz-muscovite schist, commonly with magnetite. Garnet was observed in this unit near the base of the northwestern cliffs. The rusty-weathering schist with

Figure 4.13. Northern end of the cliffs on the east side of the Notch. Photo taken from Easy Gully photo point in April, 2007.

dark albite is the Hazens Notch Formation and the silver-green to gray schist is the Fayston Formation (Thompson and Thompson (1999.) The distribution of these two units appears to be approximately as shown by these authors.

Two additional lithologies are shown within the study area by Thompson and Thompson (1999.) Greenstones are shown on the upper, western side of the study area beyond the limits of detailed outcrop mapping in this study. An aluminous member of the Fayston Formation is also mapped, but was not observed in the areas examined in this study. No fallen boulders of either of these two units were observed in the floor of the Notch.

Despite a structural and metamorphic history that involves several episodes of deformation, the structural geology within the limited bounds of the study area is relatively simple and has led to an extremely uniform fracture pattern. This will be described in some detail in Chapter 8.

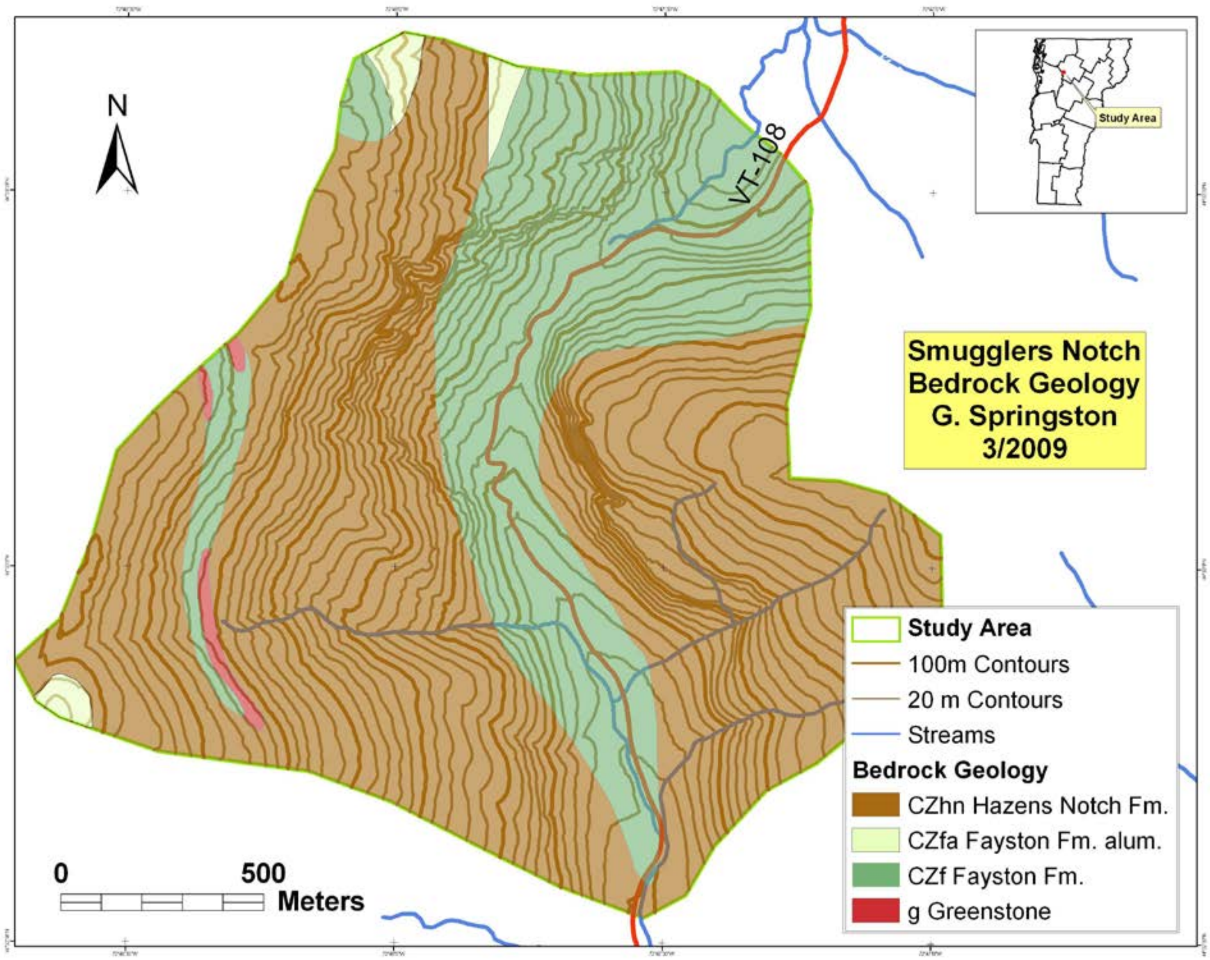


Figure 4.14. Bedrock geology of the study area. From Thompson and Thompson (1999.)

The Shaping of Smugglers Notch

Smugglers Notch owes its form to some combination of pre-glacial fluvial erosion, scouring by active glacial ice, discharges of glacial meltwater, periglacial and post-glacial weathering, landslides, and modern stream erosion. However, previous authors have differed somewhat on the extent to which each of these factors has shaped the Notch. Jacobs (1938) advocated a combination of stream erosion and glacial scour, while Christman (1956) thought that stream erosion had played only a small role. Christman (1959, p. 70) appears to have rethought his position and suggests that both processes played a role. Stewart (1961) recognized the importance of both stream erosion and glacial scouring, but in addition pointed out the importance of weathering and talus accumulation in the geologic development of the Notch. He felt that much of the talus accumulation had occurred under periglacial conditions soon after deglaciation.

The Notch probably does owe its beginnings to stream erosion. It seems likely that long-continued headward erosion by pre-glacial ancestors of the Brewster River and the West Branch had progressively lowered this section of the divide between the two drainage basins. This low spot on the divide could then be exploited by glacial ice during the many glaciations of the Pleistocene Epoch.

Scouring and deepening by glacial ice has certainly played some role in shaping the Notch. Abundant evidence for the direction of ice movement in the last glaciation is seen on the higher peaks of the northern Green Mountains in the form of glacially polished and striated rock surfaces. Ice movement was generally from northwest to southeast as indicated by glacial striations on the summit ridge of Mount Mansfield, which range from about 119° to 145° (Christman, 1959 and this study.) Striations with an orientation of 141° were measured at an outcrop on the ski slopes northwest of Madonna Peak. These too appear to represent the regional ice flow direction. By contrast, striations at two locations on Spruce Peak had orientations of 162° and 165°, directions that are approximately parallel with the trend of the south portion of the Notch. They may thus represent local redirection of ice flow through the Notch. There is also an intriguing report of glacial striations on the west side of the Notch. Jacobs (1938, p. 41) reports that "…glacial striations are still seen on the Hell Brook trail, trending generally parallel to the valley wall." As the valley trends about roughly north-south in this area, these striations seem to represent a local redirection of flow.

No other evidence was found in this or in earlier studies of glacially polished or striated surfaces in the Notch itself. The intense physical weathering, abundant landslide activity, and development of thick talus blankets at the base of the cliffs appear to have destroyed or buried any glacially scoured surfaces that may have existed.

At the end of the most recent glacial episode the Notch is likely to have been an outlet for glacial meltwaters as the ice retreated north of the divide. Although no detailed surficial geologic mapping has been undertaken south of the Notch, there must have been some amount of glacial meltwater flowing southward from the Notch. Stewart (1961) describes "lake sediments" along the Mountain road from about 900 feet elevation to about 1,200 feet. Further north on the Mountain Road he describes gravel deposits that extend from the entrance to the Toll Road up to the base of Spruce Peak. He interprets these as kame terrace deposits that formed between a remnant ice sheet in the lowland and the mountain slopes to the north and west. The lake sediments were presumably deposited in a proglacial lake that formed after additional downwasting of this ice mass.

To the north of the Notch, Christman (1959) describes a deposit of lacustrine material on the west slope at an elevation of 1,950 feet. From the location given on his Plate 3, this appears to be in or near the current beaver wetland complex located northeast of the main parking lot. Christman (1959) interprets this sand as lacustrine, implying a high-level proglacial lake formed between the mountain slopes to the south and the ice sheet to the north. Drainage would at least initially have been southward through the Notch. Because of its high elevation, the Notch would not have served as an outlet for the larger regional proglacial lake known as Lake Mansfield as this had a maximum surface elevation of only about 800 feet in this part of the Lamoille River watershed (Wright, 2003.)

In post-glacial time, the climate in the Notch was probably harsh enough to promote physical weathering through numerous freeze-thaw cycles and frost wedging of cracks. The large size of the talus accumulations below the cliffs and the lack of glacially polished surfaces on any of the cliffs suggest rather intense post-glacial weathering. Indeed, such activity continues to the present. A detailed study of mechanisms of rock-mass degradation in the Notch was undertaken by Lee and others (1997.) See Chapter 9 for further discussion of this topic.

The form of the cliffs is strongly controlled by three sets of fractures (joint sets) that intersect at near-right-angles to one another. One of the joint sets (J1) is sub-horizontal and the other two have very steep dips (sets J2 and J3). The outer faces of the cliffs on both sides of the Notch are composed of alternating J2 and J3 joint surfaces. These features will be described in more detail in Chapter 8.

Landslides, in the form of the rock falls, rock slides, and debris flows described above, have been very important agents in the post-glacial modification of Smugglers Notch. These are the principal mechanisms that have carried materials down to the valley floor, where stream processes have partially modified them.

Extensive post-glacial stream terraces in the valley bottoms both to the north and to the south of the Notch indicate that the streams have carried considerable coarse-grained material out of the Notch and off of the mountainsides. The State picnic area to the south of the Notch is built on one of these thick Holocene stream terrace deposits.

5. Landslide Classification

Landslides are defined by Sidle and Ochiai (2006, p. 1) as "…a variety of processes that result in the downward and outward movement of slope-forming materials composed of natural rocks, soil, artificial fill, or combinations of these materials." Gravity plays a dominant role in such slope failures, but water (in several ways) is almost always a critical factor. A classification of landslides is given in Table 5.1, with those common in Smugglers Notch shown in bold.

Two very distinct types of landslides or slope failures occur in the Smugglers Notch area. The first is the broad class of landslide that includes rock falls and slides, and which consists of one or more large pieces of rock detaching from a cliff and falling or sliding down a slope. Most of the boulders in the floor of the Notch appear to be the result of such rock falls and slides. The second class of landslides includes the debris flows, which are slurries of water, mud, pebbles, cobbles, and boulders that flow within shifting channels on the talus slopes below the cliffs. In the Notch, they are activated by heavy rainstorms and/or snowmelt.

Table 5.1. Simplified classification of slope movement types. Modified from Varnes (1978.) Types common at Smugglers Notch are in bold.

Type of Movement	Type of Material		
	Bedrock	Engineering Soils	
		Predominantly coarse	Predominantly fine
Falls	**Rock fall**	Debris fall	Earth fall
Topples	**Rock topple**	Debris topple	Earth topple
Slides	**Rock slide**	Debris slide	Earth slide
Spreads	Rock spread	Debris spread	Earth spread
Flows		**Debris flow**	Earth flow
Complex	Combinations of two or more types of movement		
Creep	Several types		

Rock Falls, Topples, and Slides

Rock falls, topples, and slides are landslides that involve one or more large blocks that detach from a bedrock ledge. In order to keep the terminology from becoming confusing, we need to distinguish two parts of the process: how the piece falls from the cliff, and how the piece then moves down-slope after the detachment. In the first part of the process, blocks can fall directly from an overhang, topple off by rotating outward and down, or slide off a sloping surface or a pair of sloping surfaces. Slope failures that involve a block sliding on two surfaces are called wedge failures. All of these types of rock slope failure occur on the cliffs at Smugglers Notch and are shown in Figures 5.1a to 5.1d. In this report, for simplicity, the term *rock fall* will refer to a block detaching from the cliff by any of the processes described above.

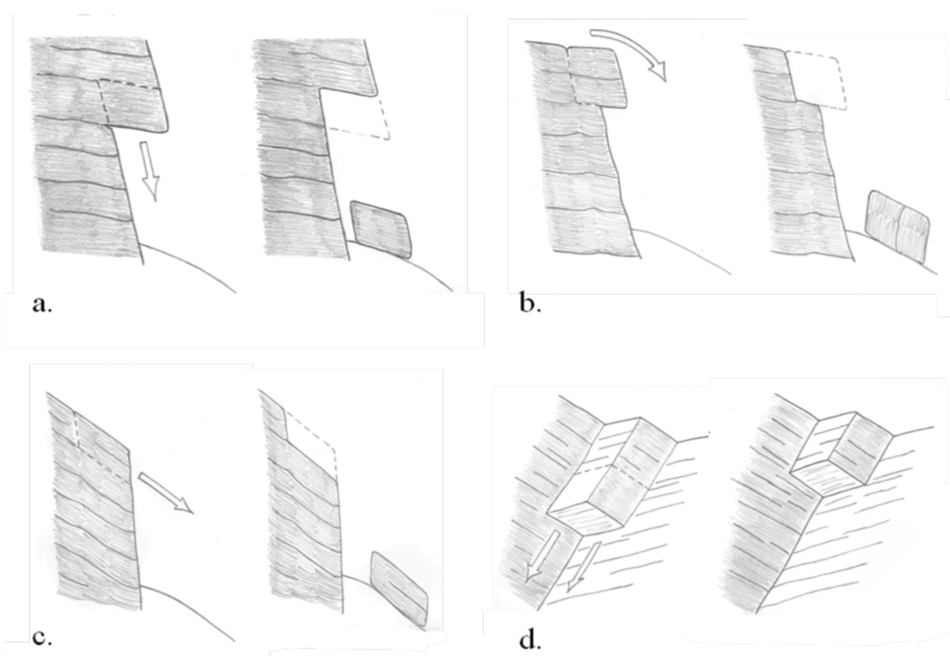


Figure 5.1. Types of rock slope failure encountered at Smugglers Notch. a) Rock fall. b) Rock topple. c) Rock slide. d) Wedge failure. Note that the rock slide fails by sliding down-dip on a

single surface while the wedge fails by sliding on two surfaces and moves downward parallel to the intersection of the two surfaces.

Figure 5.2. Overhang on cliffs on west side. Knapsack for scale. Overhangs are common on both sides of the Notch. This particular one may eventually fail by sliding or toppling due to an open joint in the left-hand side. Other overhangs serve as source areas for falls. Photo 3534a, 10/2/2007.

Once the piece is detached it may fall freely through the air and land at the base, never to move again. Far more commonly however, a block bounces off some part of the cliff below, perhaps breaking off pieces of the cliff or breaking up itself. Upon impacting the talus slope below, there is a large amount of bouncing and, if it strikes in one of the debris-laden gully bottoms, it will commonly start a rock slide of boulders and cobbles (this is the origin of the light-colored slide scars so prominent on the west side of the Notch.) We will refer to such slides composed of many pieces of rock as a *rock slide* while we will call the sliding movement of a single block a *rock block slide* (Fleming and Varnes, 1991.)

At Smugglers Notch, each of the prominent rock slides that originates below the rock chutes and/or the larger rock faces serves as a source areas for one or more of the debris flows which develop further down slope.

Debris Flows

Although debris flows occur in a variety of geologic settings around the world and vary considerably in their characteristics, they all consist of fast-moving slurries of mud sand, gravel, and boulders and other materials encountered on the descent of a steep slope.

The debris flows at Smugglers Notch are all quite similar to one other. The flows all originate along rock slide paths at the bases of the cliffs and all of the debris flows at Smugglers Notch appear to be confined to channels, which are commonly bounded by levees of imbricated boulders and cobbles. Note that these levees are deposited by the flows themselves as the rapidly flowing muddy torrent of the debris flow spills out sideways and drops part of its load. There is abundant evidence on the slopes that these flows shift locations over time in response to channel blockages and perhaps shifting patterns of rock fall. A block diagram illustrating the common Smugglers Notch debris flow morphology is shown in Figure 5.3. Upon reaching less steep terrain the debris flow can no longer transport all of the entrained material and the flow spreads out laterally, leaving behind a spatulate, steep-fronted terminal lobe or snout deposit composed of very poorly sorted bouldery, pebbly cobble gravel and woody debris. What little fine-grained material that was present in the flow has generally been washed further downstream. According to Costa (1998), the levees and steep-fronted terminal lobes are strong indications that these features should be classified as debris flow deposits rather than stream flow deposits. These features are characteristic of laminar rather than turbulent flow and are only formed by deposits that have very high sediment/water ratios. Such flows have been called *channelized debris flows* (VanDine, 1985.) The coarse-grained nature of the deposits here is also characteristic of such channelized debris flows (Cruden and Varnes, 1996; VanDine, 1985; Hungr and others, 2001.) As there appear to be no other types of debris flows here, we will call them simply debris flows.

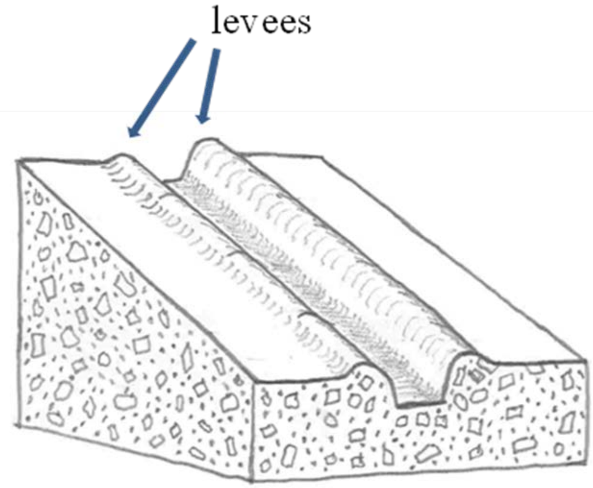


Figure 5.3. Schematic block diagram of a section of a debris flow at Smugglers Notch. Note the levees on the margins of the channel. For ease of portrayal, these are shown as continuous features in the sketch, but they are actually discontinuous, at some locations being well-developed along both sides of the channel, at other locations only on one side, and at still others being absent altogether.

Descriptions of two recent debris flows are given in Chapter 7. See especially the photos of an active debris flow channel in Figure 7.8, a levee deposit in Figure 7.9 and a steep-fronted terminal lobe of an active debris flow in Figure 7.16.

The Smugglers Notch debris flows were classified by Lee and others (1994) and Lee and others (1997) as “debris avalanches”, but these are quite clearly channelized and do not spread laterally as they descend. Also, the levees indicate a sediment-rich, but still watery flow of some sort, rather than the drier flow typical of a debris avalanche. Using the classifications of VanDine (1985) and Hungr and others (2001), these should therefore be called debris flows rather than debris avalanches.

6. Landforms

The landforms in the study area are shown on Plate 4 and in Figure 6.1 and are described below. Note that the interpretation of these landforms is an important component in the delineation of slope instability hazards to be described in Chapter 9 (see especially Plate 5 and Figure 9.1.)

Most of the study area was mapped as “mountain slope.” These are areas with moderate to steep slopes that are underlain by thin deposits of glacial till and colluvium with scattered exposures of ledge (bedrock.)

Rock ledges and cliffs are, of course, the most prominent features in Smugglers Notch. The ledges mapped in this category are the prominent cliffs that are likely to produce rock falls. There are abundant smaller ledges scattered throughout the areas mapped as “mountain slope.” Although some may occasionally contribute a falling rock, most are too low or too distant to contribute significantly to the hazard ratings.

Talus deposits are accumulations of fallen boulders at the bases of cliffs. They are widespread on both sides of the Notch (Figures 4.6 and 4.12.) Talus has accumulated to such an extent that it is impossible at present to discern the bedrock topography in the floor of the Notch. Although talus accumulation certainly occurs today, it is likely that the rate of talus accumulation was much greater under the harsh climatic conditions of late glacial and immediate post-glacial times.

Rock chutes are narrow drainage paths located in fracture zones in the bedrock. As shown in Figure 4.9, many originate on the steep mountain slopes above the cliffs and feed water and rock into the debris flow paths below the cliffs.

Debris flows have been very important agents in shaping the slopes of the Notch. However, upon reaching the valley bottom, much of the material gets swept away by stream activity and the mappable debris flow deposits are limited to four areas shown in Plate 4 and Figure 6.1 as “debris flow deposits.” These are mostly steeply sloping partial cones of debris flow materials. They include cones that have accumulated below Hidden and Easy Gullies on the west side and below Elephant’s Head Gully on the east side, as well as a large debris flow deposit in the southern part of the study area, just north of the Stowe-Cambridge town line. This last debris flow deposit differs from the others in that this is a deposit in the valley bottom while the others are steep cones on the valley wall. The debris flow paths and the usual small terminal lobes (which are too small to show on the maps) have already been described in Chapter 5 and two examples of active debris flow paths and the resulting deposits are given in Chapter 7. Note that although the debris flow deposits have some talus boulders on their surfaces, they are composed of relatively finer-grained material than the talus slopes (bouldery pebble and cobble gravel as opposed to the boulder deposits of the talus.)

Deposits of a mixture of colluvium and talus are common on the lower portions of the slopes in the Notch. Colluvium is a general name for deposits that result from some combination of slope wash (sheet erosion), soil creep, and other forms of mass wasting. In the Notch, these areas have only a limited component of talus accumulation. Because these areas are not dissected by fresh debris flows, the exposures are poor, and some may consist of ancient debris flow and/or talus deposits that have been partially buried by later colluvial activity.

Stream deposits form a narrow belt in the valley bottom along the course of the West Branch. Some of these deposits are in the present stream channel and floodplain while others are older stream terrace deposits. The alluvial fans described below are also composed of stream deposits, but are broken out separately to emphasize their indication of erosion hazard.

Two alluvial fans were encountered in the study area. Although these are not landslides, they are indicators of significant fluvial erosion hazard. An alluvial fan is a bouldery stream deposit that forms at the confluence of a steep tributary with a larger stream. A fan builds up over time as the tributary shifts back and forth due to debris jams and shifting of channels on the fan. The larger of the two fans in the area is on the lower segment of Hell Brook at the confluence with the West Branch. At present, the main channel of Hell Brook flows along the southern edge of the fan. A flood chute or secondary channel was observed in the central part of the fan and is normally dry, but has been observed to be flowing at times of high flow (flow observed on 7/24/2008 and 5/8/2009.) The southern fan is located on the lower segment of an unnamed tributary that flows into the West Branch near the southern limit of the study area. This does not appear to be as active as the Hell Brook fan.

A wetland complex containing a beaver pond is located in the northeastern part of the study area. This beaver-influenced wetland is located northeast of the main parking area in the headwaters of the Brewster River. Besides receiving surface runoff from the east, south, and west, it also receives debris flow and/or rock fall material from Jeff Gully to the west. Although there are no mentions of the wetland in the older literature, and is not shown on the 1927 or 1948 editions of the USGS Mount Mansfield 15-minute quadrangle, the beaver pond does show up clearly on the 1962 aerial photos (Plate 3.) The absence of the wetland on the older maps may be due to the mid-20th century return of beaver to the area or simply due to its small size.

Areas along the roadways or in parking areas that have been heavily shaped by human activity are mapped as “graded or filled.” These may be underlain by any of the other deposits seen in the valley bottom.

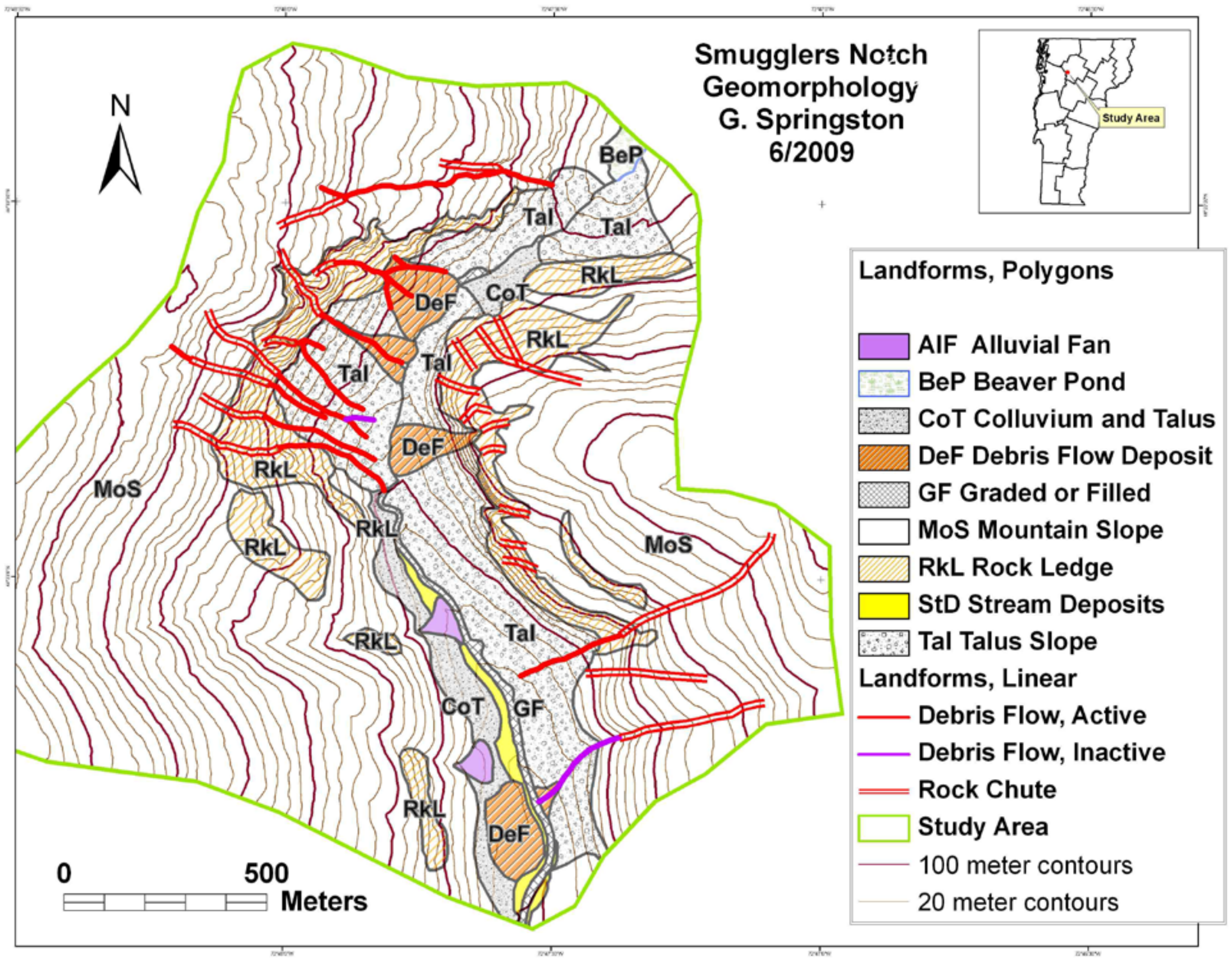


Figure 6.1. Landforms of Smugglers Notch. Classification of the landforms within the study area. This serves as the basis for the evaluation of slope instability hazards in Chapter 9. The units are defined as follows: Alluvial Fan—bouldery stream deposit at confluence of a tributary with larger stream; Beaver Pond/Wetland; Colluvium and Talus—slope wash deposit and some talus at base of steep mountain slope; Debris Flow—steep accumulation of debris flow deposits, commonly mixed with talus; Graded or Filled—area modified by human activity; Mountain Slope—moderate to steep slope of glacial till and colluvium with scattered bedrock; Rock Chute—drainage path that feeds water and rock to debris flow below; Rock Ledge and Cliff—steep to overhanging slopes underlain by bedrock; Stream Deposits—narrow belt in valley bottom underlain by stream gravels; Talus—deposit of fallen boulders at base of cliff.

7. History of Landslides in Smugglers Notch and Vicinity

Near the northern opening of the notch, and about four miles from Carlton's hotel, in Cambridge, and about eight miles north of the village of Stowe, is a large rock, about sixty feet in circuit, which became detached from its parent bed far up the mountain side, about fifty years ago, and came thundering down into the valley, laying waste the giant trees and whatever chanced to be in its downward path, and producing a rumbling sound not unlike an earthquake, which was heard afar off, and shook the hills for miles around.

Hitchcock and others, 1861, Geology of Vermont, p. 881

Many slope failures have occurred in Smugglers Notch, with the earliest record from about 1808. All known events are listed in Table 7.1. Sources are listed in the table. As excellent descriptions of many of these have already been given by Hagerman (1975) and Lee and others (1994), only selected events from prior to the 1990s will be described in detail.

Table 7.1. High-elevation landslides at Smugglers Notch and Mount Mansfield. Many are described in Hagerman (1975) and Lee and others (1994.)

1808 or 1811 rock fall involving 2 large rocks; one, apparently the one known as"Barton's Rock", was 30 x 16 feet (Hagerman, 1975 and Hemenway, 1871.)

Spring or summer, 1827; landslide on west side of Mount Mansfield (diary entry cited by Hagerman, 1975, p. 102.)

July 27, 1833; landslide of some sort (Hagerman, 1975.)

1848; landslide that ran "…nearly three miles from The Chin to the mountains' base" on the Cambridge side (Hagerman, 1975, p.17.)

Early October, 1868; Rock fall and rock slide near Big Spring (Daily Free Press, 1868; Hemenway, 1871.) A stereopticon slide at Vermont Historical Society entitled "Slide looking up Notch, Stowe, Vt.", published by L.G. Burnham in 1873 appears to show this slide.

June 3, 1887; major slide on the Underhill side of Mount Mansfield. See the vivid description in Hagerman (1975, p. 17 -18.)

August 11, 1892; landslide on the west side of Mount Mansfield "40 rods wide and nearly a mile in length" (Hagerman, 1975.)

Spring, 1910, winter of 1910/1911 or spring, 1911; fall of King Rock from west side of Notch, 6,000 tons (Anonymous, 1911; Baskerville and others, 1993.)

1925; postcard at Vermont Historical Society showing "[t]he rock that fell in Smugglers Notch in 1925" in the middle of the road. Year is hard to read—it could be 1935.

August, 1955; landslide on west side of Mount Mansfield (Christman, 1959)

(Continued next page)

Table 7.1 continued.
Spring, 1964; rock fall at Elephant's Head (Hagerman, 1975; Vermont Geological Survey files.)

May 24 – 25, 1966; rock slide north of the height of land (Hagerman, 1975; Burlington Free Press, 1966.)

May 20, 1969; debris flow originating from the west side of the Notch. This event caused the road to be closed for about a week, soon after the road had been opened for the season (Hagerman, 1975; Burlington Free Press, 1969.)

1973: Report of destruction or damage to the roof of the stone information shelter in the Notch (Lamoille County Regional Planning Commission, 1995, p. 44.) No other information on this event has been found to date.

August 10, 1976; rock slide and heavy erosion due to remnants of Hurricane "Belle." Damage was on the Cambridge side of the Notch (north of the height of land) (Stowe Reporter, 1976.)

July 13, 1983; rock fall, 1 or more blocks totaling 11,500 tons or 10,400 metric tons (Baskerville and others, 1988; Lee and others, 1997.)

June 6 to 7, 1984; Heavy rains resulted in extensive damage in the Notch due to debris flows (Tim Wilson, Vermont Agency of Transportation (VAOT), personal communication, January, 2008 and Barre-Montpelier Times Argus, June 7 and 8, 1984.) The Times Argus reports widespread damage throughout central and northern Vermont and the June 8 edition shows a photo of damage to Rt. 108 on the Cambridge side.

May 22, 1986; 12 or more rock falls and debris avalanches, with the largest estimated to include about 327,000 cubic yards or 250,000 cubic meters (Lee and others, 1994, 1997.)

September 13, 1986; fall of a three-meter diameter block from an overhang on the cliffs on the west side of the Notch. Occurred after two days of heavy rain (Lee and others, 1994.)

Summer, 1988 or 1989, Rock slide off of east slope of Notch, north of height of land (Tim Wilson, Vermont Agency of Transportation, personal communication, January, 2008.)

July 4, 1989; rock fall north of Elephant's Head (Lee and others, 1994.)

September 11, 1993; rock fall in Hidden Gully associated with a rescue operation, 1 person injured (Neil van Dyke and Burlington Free Press, 1993.) Not tallied in the monthly frequency histogram as it was not a natural rock fall.

July 4, 1994; rock fall at "S" turns. Originated from west side of Notch (Tim Wilson, VAOT, personal communication, January, 2008.)

Early summer, 2005, landslide along slide scar north of the main parking lot. Originated from the west side of Notch and did not reach road (Tim Wilson, VAOT, personal communication, January, 2008.)

June 27 – 28, 2006; debris flow in "Hidden Gully" (this study.)

(Continued next page)

Table 7.1 continued.

July, 2006; rock fall south of King Rock (Tim Wilson, VAOT, personal communication, January, 2008.)

Early August, 2006; rock fall and debris flow in "Easy Gully" (this study.)

November 14 or 15, 2006; debris flows at the "S" turns on Vt. Rt. 108 resulting from heavy rain (this study.)

October 4, 2007; rock fall at cliff on north side of Easy Gully (report from Vermont Department of Forests, Parks and Recreation caretaker, October 4, 2007.)

October 21, 2007; rock block slide on east side of Vt. 108, north of height of land (this study.) Further debris washed down onto the road about a week later (Tim Wilson, VAOT, personal communication, January, 2008.)

Additional information on road damage related to landslides in the Notch is shown in Table 7.2. This contains events in the Notch that required response by the crews from the VAOT staff. The picture that emerges from this table is that landslides are nearly annual events.

As Rt. 108 is closed in winter, the "early spring" reports in Table 7.2 could refer to material that came down at any time since the road was closed late in the previous year. However, the effects of the spring thaw on the cliffs and, to a lesser extent, snow avalanches are the most likely causes.

Table 7.2. VAOT data listing the season, year, and mileage north of the Stowe-Cambridge town line, and type of damage. MM = Mileage starting at Stowe-Cambridge town line. Only events not already listed in Table 7.1 are shown. From Scott Rogers, Assistant Director of Operations, VAOT (April 16, 2008 email communication.)

Date	**MM**	**Comments**
Summer 1995	0.6	Large boulder in road
Spring 1999	0.1	Trees, mud
Early summer 2000	1.4	Boulders, used hoe ram to break up.
Summer 2001	1.0	Rocks and debris in pullout
Fall 2002	1.4	Trees
Fall 2002	0.1	Stones debris
Fall 2003	1.0	Rock slide
Fall 2004	1.0	Trees
Fall 2005	1.4	Trees
Early spring 2006	1.0	Debris in roadway
Early spring 2007	1.0	Debris in roadway
Annually	0.0 - 2.0	Once or twice a year reports of debris (small to medium boulder) Jun – July

The tremendous boulders in the floor of the Notch have long been of interest to visitors. One of the large ones near the site of the Notch House (near Big Spring) is known as Bingham's Rock, and is shown in Figure 7.1. This boulder fell long before the 19th century, as evidenced by an accumulation of soil on the top and the trees which had grown on top (Hitchcock and others, 1861.)

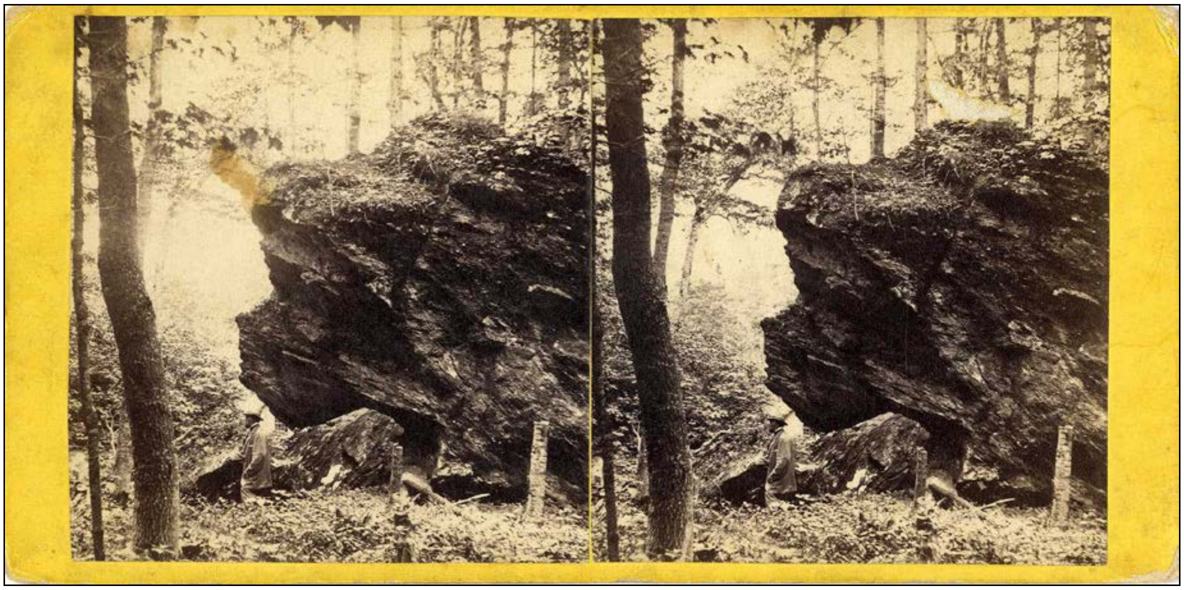


Figure 7.1. Stereoview of Bingham's Rock, Smuggler's Notch. Labeled "No. 158. Green Mountain Scenery, Stowe, Vt. Photo by Heywood. Published by Hervey Friend & Co., Gloucester, and 335 Washington St., Boston, Mass. Bingham's Rock." Landscape Change Program Image LS05221. Note man on left below rock and window of Notch House behind him. Courtesy of Special Collections, University of Vermont Library.

Rock Fall of 1868

> *A terrible avalanche of rocks recently occurred near the Notch House, on Mt. Mansfield. One of them, weighing more than one hundred tons, fell, bounding and crashing its way over and through the forest, a thousand feet or more, cutting the trees off like pipe stems, till it finally lodged within ten rods of the house, and near it , another, some twenty feet or more square, stands up like a tower, while other small ones have left their traces in different directions.*
>
> Daily Free Press (Burlington), October 19, 1868, evening edition.

The above quote is the first fully documented rock fall event in the Notch. The Notch House was a short-lived inn built by W.H. Bingham at the site of Big Spring. The path of the boulder is shown in Figure 7.2 and the Notch House is shown in Figure 7.3. Although it has not been possible to identify the section of the cliff seen in Figure 7.2, the boulder clearly came from the cliffs just to the north and above Big Spring.

Figure 7.2. Stereoview of a rock fall path in Smugglers Notch taken in 1873. This is probably the path taken by the October, 1868 rock fall, although the author was unable to match this view with any of the Smugglers Notch cliffs. Note the figure of a man visible just above the light-colored boulder in the middle-distance. Image courtesy of Vermont Historical Society.

Figure 7.3. View of the Notch House (at the present-day Big Spring) with the cliffs of the eastern side of the Notch in the background. The 1868 rock apparently fell from the cliffs to the right of

and above the Notch House and crashed down just behind it. Landscape Change Program Image LS05528. Courtesy of Special Collections, University of Vermont Library.

The Fal1 of King Rock, December, 1910

The next recorded event in the Notch itself is the fall of King Rock. Since its story is well described in Hagerman (1975), it will not be repeated here, except to say that there is some controversy as to the date of the fall. Research by Wendy Parrish of the Stowe Historical Society suggests that “about” December, 1910 is the most likely time for the rock fall (February 28, 2008 email communication from Wendy Parrish.) The cliff shown in Figure 7.4 is the Cass’s Gully area, with the rock fall source area on the cliff to the right of the prominent shadow. Figure 7.5 shows the boulder as it landed. Although the Notch Road did not at that time extend entirely through the Notch, it appears that buckboards could make it up to the present day “S” turns from the south.

Other Early 20th Century Slope Failures

The next recorded event is shown in Figure 7.6. The road through the Notch was completed in 1921 and this image shows a large boulder that fell in 1925 (or possibly 1935 as the date is hard to read.)

One event that would have been expected to result in rock fall or debris flow events is the great rainfall and flood of November 3 and 4, 1927. All we know is that if slope failures occurred up in the Notch they did not prevent the road from remaining open, as it was the only road connection between Stowe and the rest of the state for many days and the road saw very heavy truck traffic (Bigelow, 1934.)

Eyewitness Reports of Two Landslides in the 1980s

Only two eyewitness reports of landslides in Smugglers Notch are known. One involved a rock fall event and the other involved debris flows. In both cases, the witnesses fortunately escaped unharmed.

The first account is that of Mr. Dan Rogers of Jeffersonville, who witnessed the rock fall event of July 13, 1983 (see Table 7.1). According to the account in the Morrisville, Vermont News and Citizen for July 28, 1983, Mr. Rogers was running up Rt. 108 when he heard a “sonic boom.” About 60 seconds later, boulders came crashing down through the trees ahead of him. He then saw boulders rolling out across the road (Baskerville and others, 1988, p. 6).

The second account involves the May 22, 1986 debris flows (see Table 7.1). Lee and others (1994) report that Mr. Brian O’Toole of Cambridge was driving southward through the Notch during the heavy rainstorms late on the night of the 22nd. Travel became difficult as he tried to descend from the height of land and he finally had to abandon his car due to mud and gravel deposits coming across the road. As he struggled southward on foot he apparently walked through or around these flows. The West Branch was out of its banks in places and travel was very difficult. He eventually was picked up by a State Police car somewhere south of Big Spring.

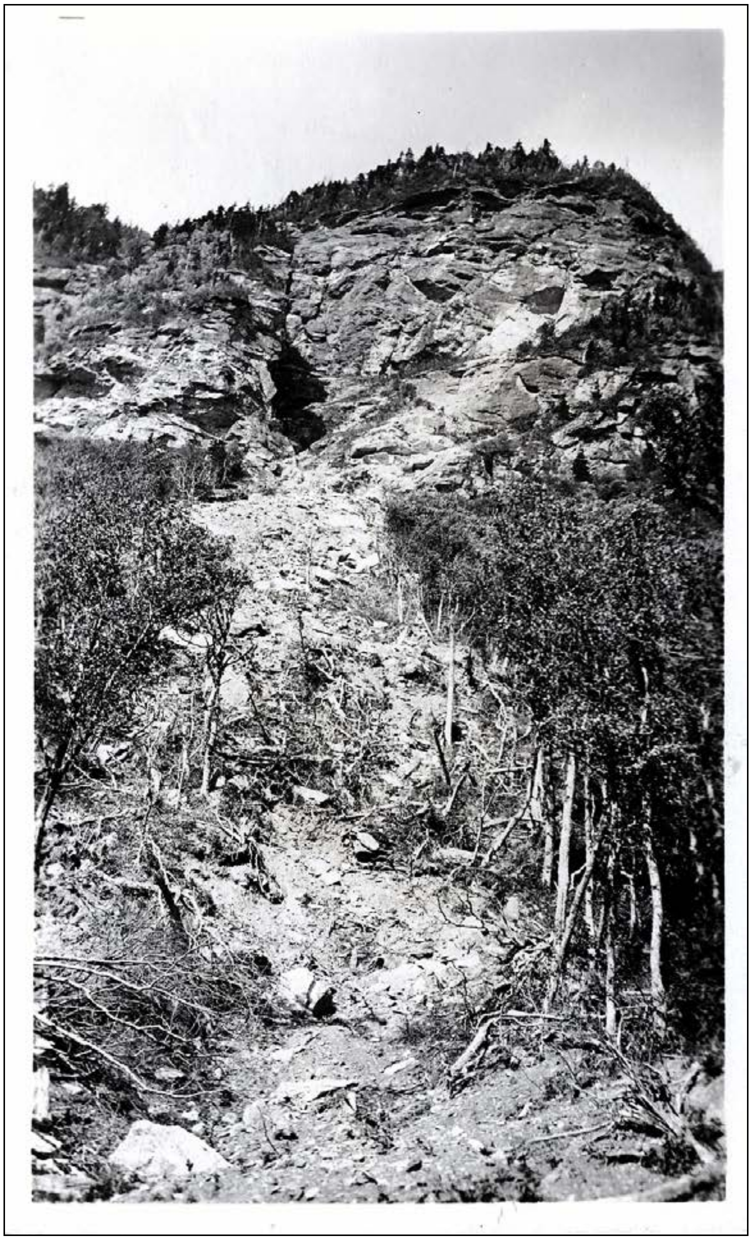


Figure 7.4. This is the scar left by the fall of King Rock, sometime in December of 1910. The source of the block appears to be the section of cliffs shown in the background. This is the face to the right (north) of Cass's Gully. The Cass's Gully area is still today a major source of rock fall and debris flow material.

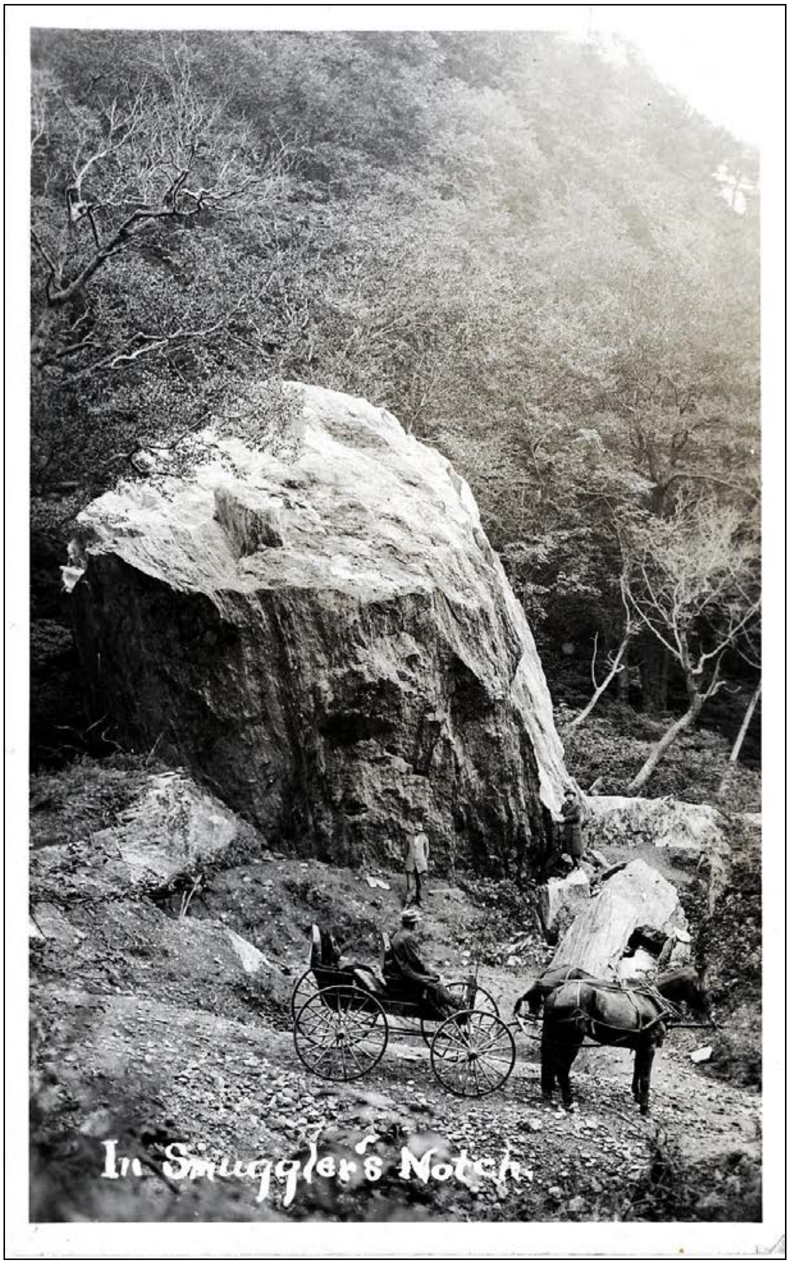


Figure 7.5. King Rock in 1911. Photo courtesy of Stowe Historical Society.

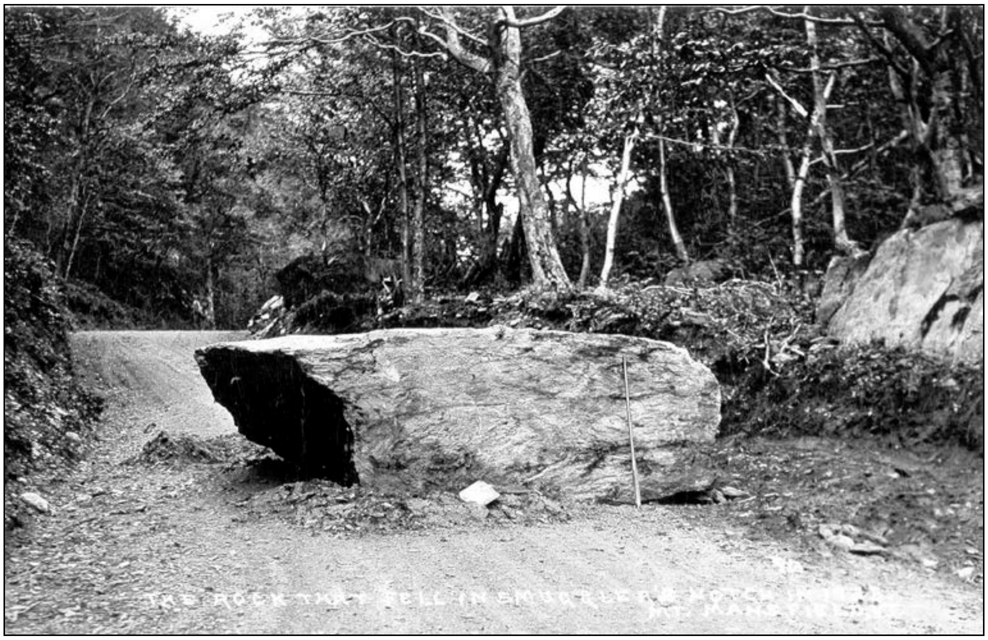


Figure 7.6. Fallen block in Smugglers Notch Road, about 1925. The road had been completed through the notch only about 4 years previously. Note the shovel at the base of the block and the iron bar at right. Image courtesy of the Vermont Historical Society.

Hidden Gully Debris Flow, June 27 or 28, 2006

Hidden Gully is a prominent fracture-bounded rock chute on the west side of the Notch. As described in Chapter 6, there is a well-defined partial cone of debris flow deposits that has built up at the base of this feature. The current debris flow channel is one of the most active in the Notch. It reaches the valley bottom at a small pull-out on the west side of Rt. 108 (Figure 7.7.) The VAOT has repeatedly cleaned material out of this location (Tim Wilson, January, 2008, personal communication.) On June 27 or 28, 2006 a heavy rainstorm resulted in a large flow of runoff from the rock chute above (see Chapter 8 for a discussion of the rainfall that led to this debris flow event.) Upon reaching the steeply sloping talus and debris flow deposits, the flow of water mobilized pebbles, cobbles, and boulders up to three feet across, sweeping down the channel, which is about 900 feet long (Figure 7.8.) A field visit on July 5, 2006 revealed fresh levee deposits, and numerous scars from recent and older boulder impacts (Figure 7.9.) There was no indication that the debris originated up on the cliffs, although the heavy rains could possibly have swept any traces away (Figure 7.10.)

Figure 7.7. Looking west at base of Hidden Gully on the west side of Rt. 108 at the debris fan formed by the recent debris flow. Orange field book on fan for scale. Debris is removed by VAOT after each flow. July, 2006.

Figure 7.8. Looking up the recently active Hidden Gully debris flow path. Note levees of coarse debris on both sides. July, 2006.

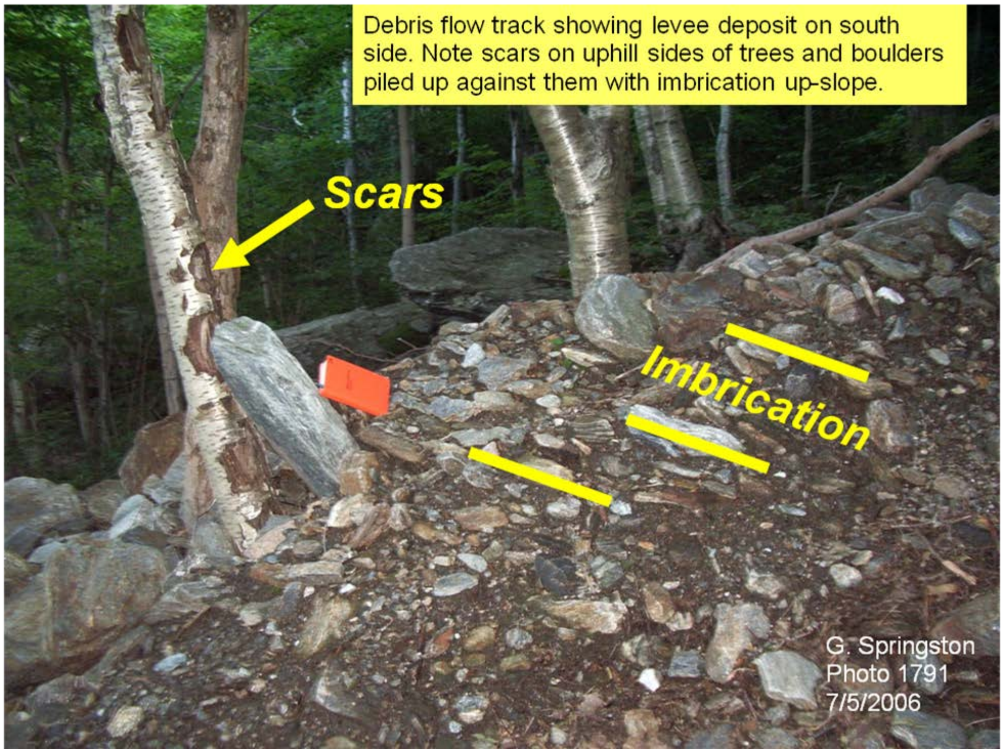


Figure 7.9. Debris flow track showing levee deposit on south side. Orange field book for scale. Note scars on uphill sides of trees and boulders piled up against them with imbrication up-slope.

Figure 7.10. Bedrock cascade above talus/debris flow deposits. Lower end of rock chute that feeds the Hidden Gully debris flow. There was no indication that debris had originated up on this bedrock section. Instead, it appears to have been remobilized from the talus and debris flow deposits below this section. July, 2006.

Easy Gully Rock Fall of August, 2006

On August 14, 2006 Neil Van Dyke of the Stowe Mountain Rescue Service reported a recent landslide at Easy Gully on the west side of Smugglers Notch. The flow followed a pre-existing track that is clearly shown in the center of Figure 4.7 and on the right-hand side of Figure 4.10. A large boulder that lodged partway down the slide scar is shown in Figure 7.11. Mr. Van Dyke had learned of the rock fall from website postings by rock climbers and visited the site on August 13. He stated that the fall occurred “probably within the last several days.”

At the upper end, the landslide is best described as a rock slide. This extends down from about 2,940 feet elevation southeast down to 2,480 feet at the large boulder. The slide then turned south-southeast and extends down at least to 2,800 feet elevation. Although this current landslide activity did not extend down to Route 108, earlier ones on this track have reached the road.

The landslide consists of coarse debris ranging from gravel up to very large boulders. Using the Cruden and Varnes (1996) classification, this was a rapid to extremely rapid, rock fall and rock slide.

The largest boulder measured about 40 feet long, 23 feet wide, and 9 feet thick. The weight is estimated to be on the order of 600 tons.

The large block rests on a fresh deposit of loose, very poorly sorted angular pebble to boulder gravel. A smaller boulder under the lower end of the large block appears to key it into place and to rest a bedrock ledge exposed several feet to the south, suggesting that the debris flow is only a few feet thick here. The surface of the landslide at the block is inclined at 35 degrees to the horizontal with the overall slope of the landslide above the block about 38 degrees.

The source area for the rock fall is an area of overhangs to the north of Easy Gully (Figure 7.12.) By examining the area above the large block we identified a section of the south wall of the ravine where one of the boulders struck the wall and bounced off (Figure 7.13.) Based on the height of the impact marks above the floor of the ravine, the block may have tumbled as it fell. Above this we saw a spot on the west wall of the ravine where the boulder fell from an overhang at least 40 feet above the base of the cliff. It appears to have bounced off a projecting ledge prior to reaching the base of the cliff. It then tumbled or slid down along with the debris flow, bouncing off the south wall as described above.

Meteorological conditions that may be related to this rock fall are discussed in Chapter 9.

Figure 7.11. Block that fell from cliff in early August, 2006. Climber at right for scale. Photo taken August 18, 2006.

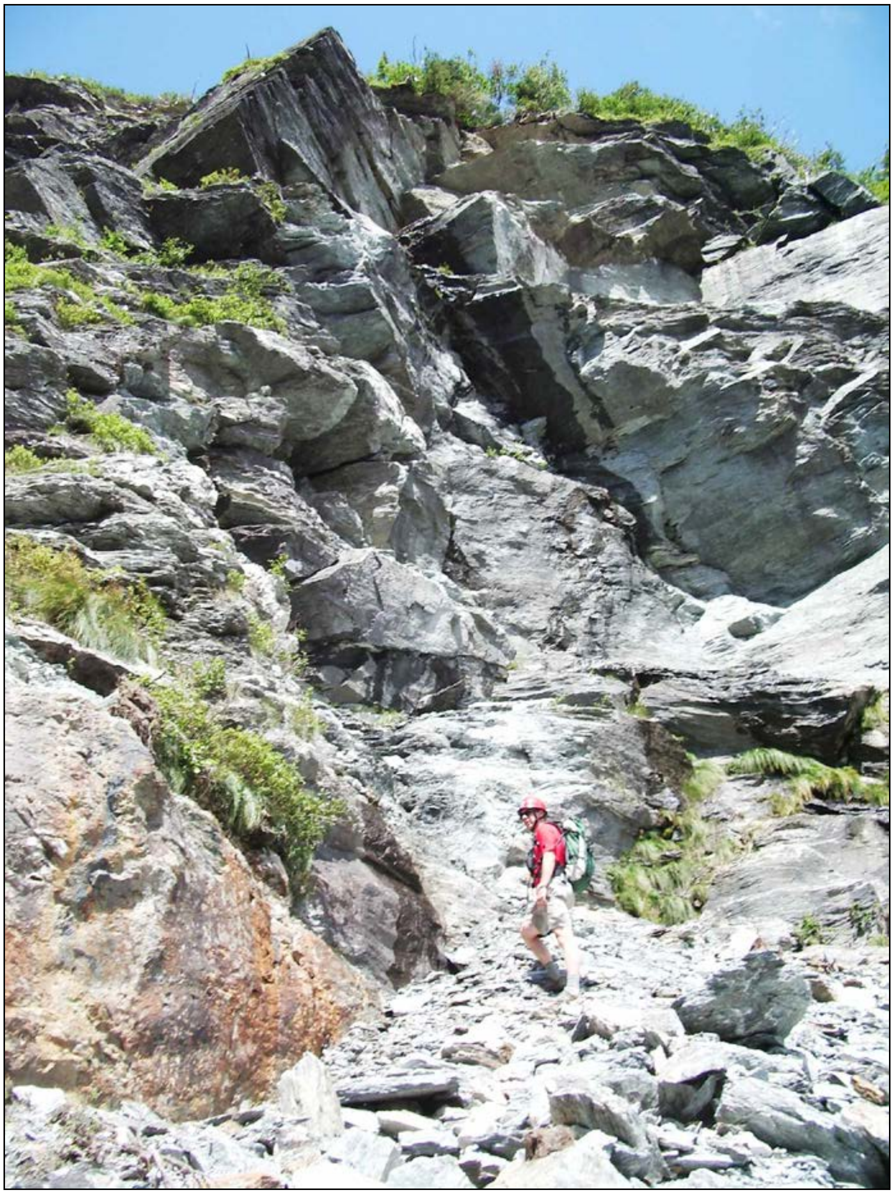


Figure 7.12. Looking northwest at overhanging ledges to north of Easy Gully. Source area for rock fall.

Figure 7.13. Easy Gully, August 18, 2006. White powdered rock on south wall of Easy Gully where falling rock impacted before coming to rest in background (above head of climber.)

November 14 or 15, 2006 Debris Flow

This is a relatively minor debris flow event that occurred along a prominent debris flow track below the cliffs south of Cass's Gully (Figure 7.14.) This is an important example of active slope instability above the "S" turns as it is at least currently one of the most active of the debris flow tracks. In the November, 2006 event, snow was present on the mountain, but temperatures above freezing and heavy rains in the preceding days led to heavy runoff (the triggering of this event is discussed further in Chapter 9.) The result was a debris flow event that carried boulders down onto the terminal lobe of the flow and swept gravel and sand out onto Route 108 (Figure 7.15.) The flow deposited fresh material on parts of the levees and scoured the lower portions of trees on the terminal lobe of the debris flow (Figure 7.16.)

Figure 7.14. Looking up the track of the November, 2006 debris flow described above. Orange and black pack for scale. Photo taken from the terminal lobe of the deposit shown in Figure 7.16.

Figure 7.15. Debris flow that reached Vermont Rt. 108 at "S" turns. This slope failure occurred during a rain and snowmelt event of November 14 or 15, 2006. Snout of debris flow in center background.

Figure 7.16. Looking downhill at the terminal lobe or snout of the November, 2006 debris flow. Orange and black pack for scale. Note scour on tree at left and Vermont Rt. 108 in background.

October 21, 2007 Rock Block Slide

This event occurred on the east side of Rt. 108 to the northeast of the main parking lot. Two large blocks of bedrock detached from the ledge about 91 feet above the road and slide down the 50° slope onto the road. When broken up, the blocks and associated debris totaled approximately 35 cubic yards (George Decell, VAOT, personal communication, October 22, 2007.) Further debris washed down onto the road about a week later (Tim Wilson, VAOT, personal communication, January, 2008.) The initial slide occurred soon after a heavy rainstorm. See the discussion of this event in Chapter 9.

Figure 7.17. Site of October 21, 2007 rock block slide. Looking up at slide path after road had been cleared.

Figure. 7.18. Looking down the path of the October 21, 2007 rock slide. Although much of the fallen material was trucked away, some was pushed over the far side of the road.

Repeat Photography for Tracking Changes on the Cliffs Over Time

As part of this study, historic photos were compared to modern ones taken from similar locations. As an example, Figure 7.20 compares a photo taken in 1921 with one taken in 2007. The only substantial change that is visible is on the lower right-hand side of the Elephant's Head buttress, where a block fell in the spring of 1964 (Table 7.1.) Additional comparisons should be undertaken with some of the other historic photos, such as Figure 7.21, which provides a good view of the west cliffs.

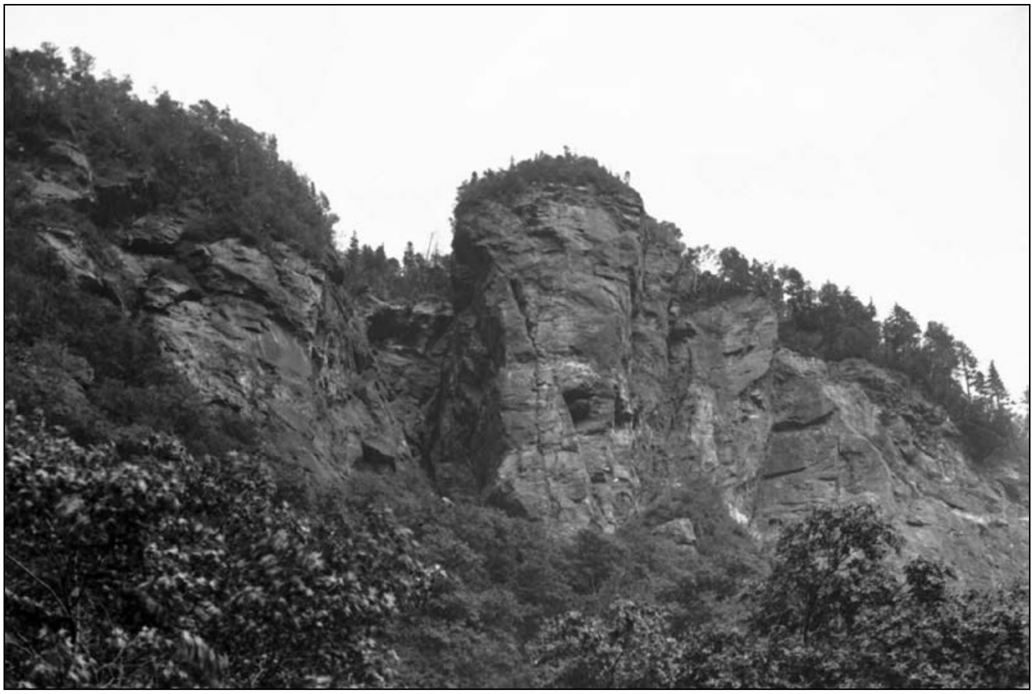
For tracking changes in the cliffs over time, it will be important to build up a set of high-resolution images of the cliffs, taken from known photo-monitoring stations. The best times of year for these photos are in the spring and in the fall. The spring photos should be taken prior to leaf-out but after snowmelt is largely completed (typically early May) and in the fall after the leaves are off the trees in late October or early November. Table 7.3 indicates the best stations encountered in this project that can be accessed without technical climbing skills.

Figure 7.19. Source area for October 21, 2007 rock slide. This is part of a long set of ledges containing abundant loose material. Future falls and slides from this area onto Vt. Rt. 108 are to be anticipated.

Table 7.3. Locations for repeat photography for tracking changes on the cliffs over time.

The top of the talus at the base of Elephant's Head at the gully on the north side. Excellent views of the west side showing the slopes south of Easy Gully.
The overlook above Elephant's Head. Good views of the west side from Easy Gully south.
Small pull-off opposite main parking area. Excellent views of the west side from Easy Gully northward.
The top of the talus at the base of Cass's Gully. Excellent views of the east side from Elephant's Head southward.
The top of the S-turns on the road, just below the debris flows from Cass's Gully. Gives closer view of Elephant's Head, but one that is somewhat obscured by trees.
The top of the talus at the base of Easy Gully. Views of the large northern promontory on the east side.

A.



B.

Figure 7.20. Elephant's Head in 1921 and in 2007. A.) 1921. Landscape Change Program Image LS06988. Courtesy of the Vermont State Archives. B.) July, 2007.

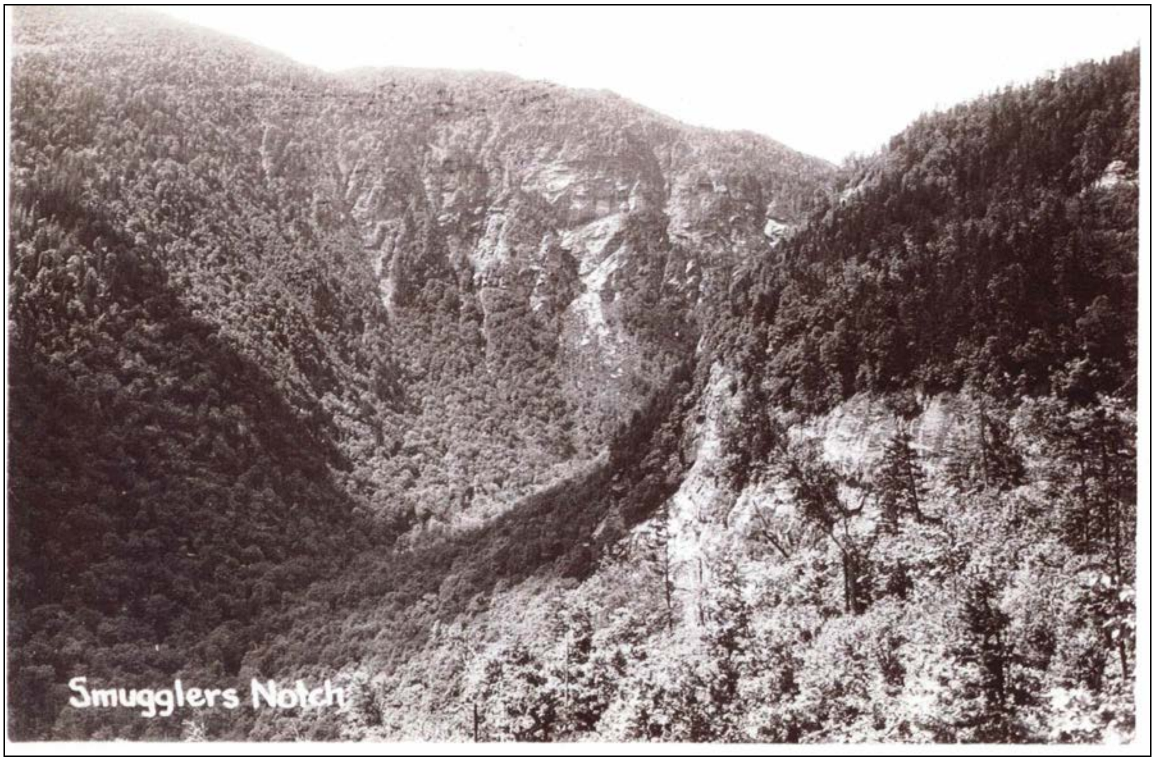


Figure 7.21. Early 20th century view of the west cliffs from south of Elephant's Head. Photo courtesy of the Stowe Historical Society.

8. Structural Analysis of Rock Masses

The structural geology of the rocks of the Hazens Notch and Fayston Formations at Smugglers Notch is relatively simple. This is at least partly a consequence of the location of the site on the axis of the large-scale structural feature known as the Green Mountain Anticlinorium (Christman, 1959.)

Two of the three fracture sets that serve to define the geometry of rock masses on the cliffs at Smugglers Notch are controlled by ductile metamorphic fabrics, which vary little in their orientations within the study area. These three sets of joints are illustrated in Figure 8.1, a sketch of an idealized outcrop from the study area. The actual outcrops in the Notch are in some spots almost as blocky as the illustration suggests.

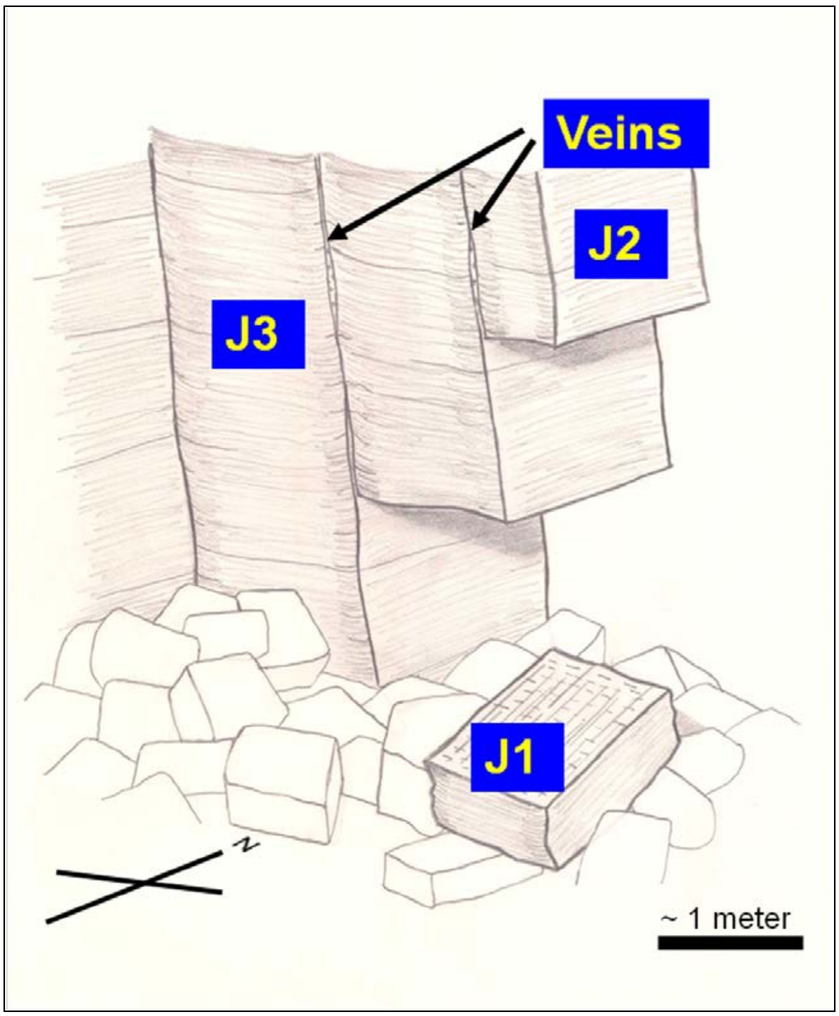


Figure 8.1. Sketch of fracture geometry on an idealized outcrop at Smugglers Notch. J1 = foliation-parallel joints with 0.6 – 2.1 m spacing. J2 = persistent joints developed parallel to a spaced cleavage that commonly is filled with quartz-feldspar +/- carbonate veins, 0.9 – 1.8 m spacing. J3 = persistent, unmineralized joints with 0.9 – 1.8 m spacing.

Orientations of the joint sets are shown in the stereonets in Figures 8.2 through 8.4. Figure 8.2 shows all joint measurements plotted as poles to planes on a lower-hemisphere equal-area net. Note that there are three strong clusterings. These are further accentuated on the contoured stereonet in Figure 8.3. As part of a preliminary analysis, the area was broken up into eastern and western subareas, and then again into smaller subareas, but the same pattern seen in Figure 8.2 was present in each. Therefore, for simplicity the data is presented in aggregate. There also appears to be no significant difference in fracture orientation between the two formations.

The first ductile feature is the prominent foliation or schistosity. One the crest of the Green Mountain Anticlinorium this schistosity has gentle to horizontal dips. Although this foliation is a fabric formed during metamorphism, the joints associated with it (Set J1) appear to have formed quite late in the geologic history, post-dating the other two sets of joints. The spacing of these joints is commonly 2 to 7 feet (0.6 – 2.1 meters.) For more detail on the joint spacing of this set, see below. They are unmineralized and are commonly the shortest of the three joint sets. These foliation-parallel joints serve as detachment surfaces for slides, topples, and falls.

The second set of ductile features is a pervasive spaced cleavage. The orientation of the poles to the cleavage planes are shown in Figure 8.4a. This is a metamorphic fabric that formed late in the deformation history of these rocks. The spacing is about 3 to 6 feet (0.9 – 1.8 m.) Joints that formed parallel to the cleavage are commonly filled with quartz-feldspar veins that in some instances contain brown-weathering carbonate mineral. A prominent set of joints (J2) forms parallel and coincident with this cleavage. These J2 joints, along with the J3 joints described below, are prominent cliff formers and lead to the formation of prominent towers and buttresses.

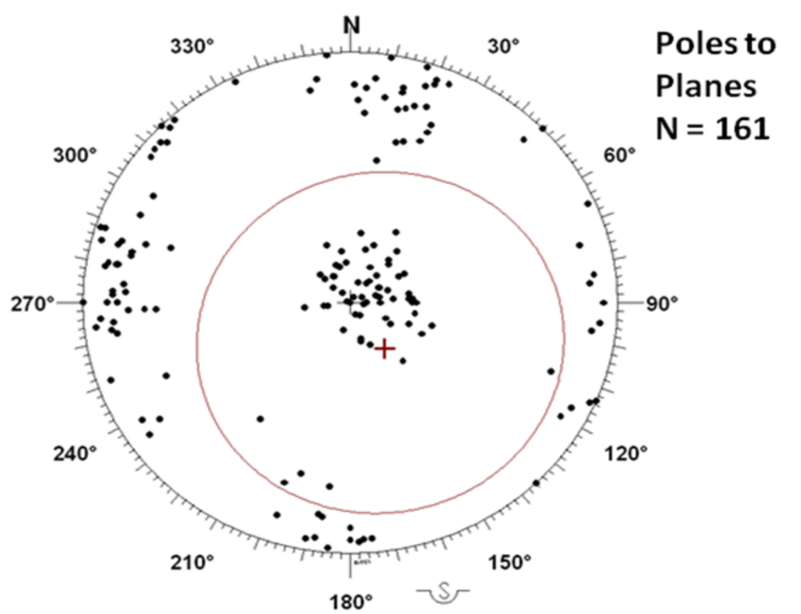


Figure 8.2. Equal-area diagram (lower hemisphere) showing poles to planes for all joints measured in this study. The same data is contoured in Figure 8.3.

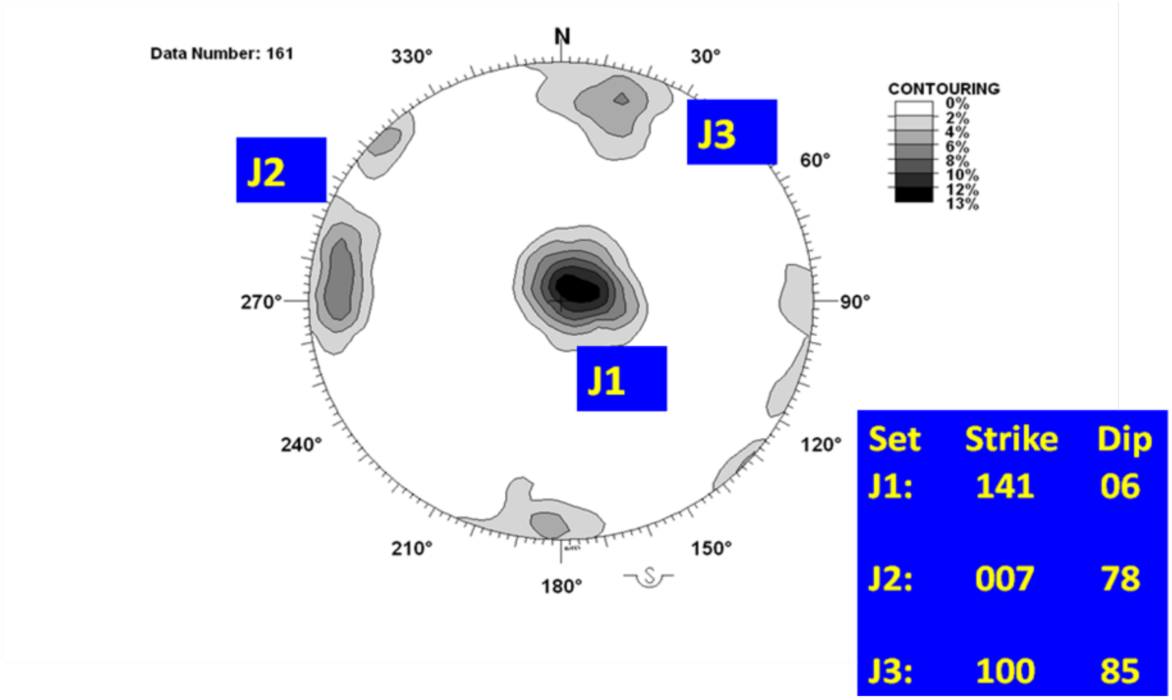
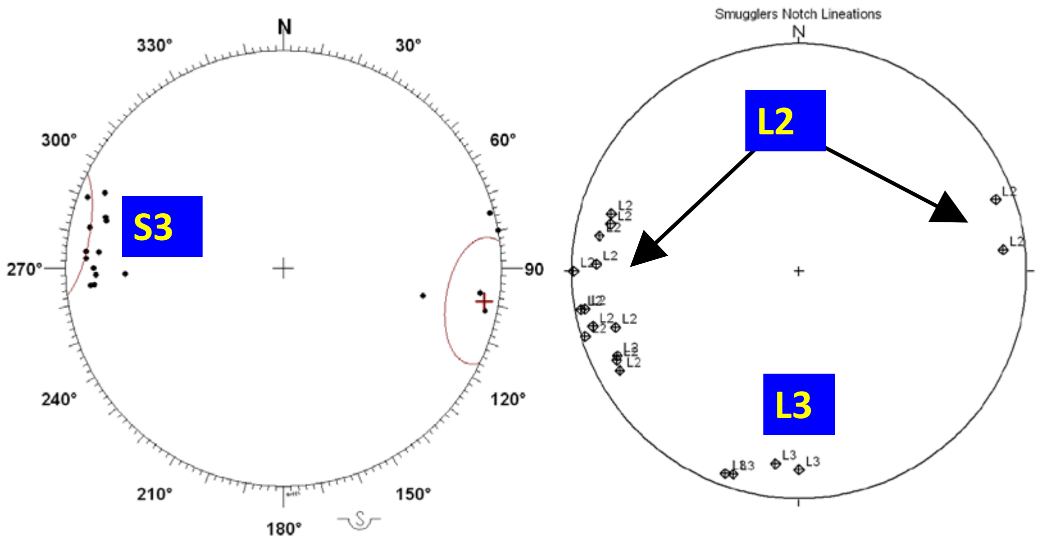


Figure 8.3. Contoured plot of all joints shown in Figure 8.2. The joint sets J1, J2, and J3 are illustrated in Figure 8.1 and described in the text. Orientations of the sets are given in the box in the lower right of the figure.

This vein-filled spaced cleavage appears to be the same feature that Lee and others (1994) interpreted as pegmatite-filled faults. These features are well exposed in many of the outcrops in the study area and were carefully examined. No offsets were observed, and this study finds, as did Christman (1959) and Thompson and Thompson (1999), that these features represent a type of cleavage.

The third set of features (J3) forms approximately perpendicular to the foliation and the spaced cleavage. They do not appear to have their orientation directly controlled by any ductile structures (as was the case with the joints that form parallel to the foliation and parallel to the spaced cleavage.) It was initially thought that the J3 set might form parallel to the L2 quartz rods and mineral lineations shown in Figure 8.4b, but analysis of individual sites shows considerable divergence. As already mentioned, these, along with Set J2, are prominent cliff-formers.

Based on cross-cutting relationships of the joints, those parallel to the spaced cleavage (Set J2) appear to have formed first, followed by Set J3, and then Set J1 (the foliation-parallel joints.)



a. b.

Figure 8.4. Additional planar and linear features for the study area shown on an equal area plot (lower hemisphere.) a.) Poles to S3 spaced cleavage (J3 forms parallel to this.) b.) Lineations: L2 quartz rods and mineral lin. and L3 crenulation axes parallel to intersection of S3 on S2.

As joint spacing is an important factor in determining the maximum block size that can be detached from a cliff, close attention was paid to this during the field mapping. It was relatively simple to note spacings for the steep joints. However, most of the field exposures only permitted access to the lowermost of the horizontal joints. As there are abundant overhangs on the upper parts of the cliffs, especially on the west side, it was thought important to see if the joint spacing was greater in the upper parts of the cliff. Therefore, two joint profiles of Set J1 (the sub-horizontal, foliation-parallel joints) were surveyed on the northwest cliffs at the locations shown in Figure 8.5. a station was established in the pull-ff across from the main parking lot, vertical angles were measured with a Total Station, and distances were measured with a laser rangefinder. Using trigonometry, the joint spacings were reconstructed. The frequency histograms in Figure 8.6 show the frequency of joint spacings for Set J1. This figure compares spacings seen in the upper 105 feet or 32 meters of the cliff with those in the lower 110 feet or 33.5 meters. The median spacing of the upper joints is 2.4 feet and the median of the lower joints is 2.9 feet. This does not appear to be a significant difference.

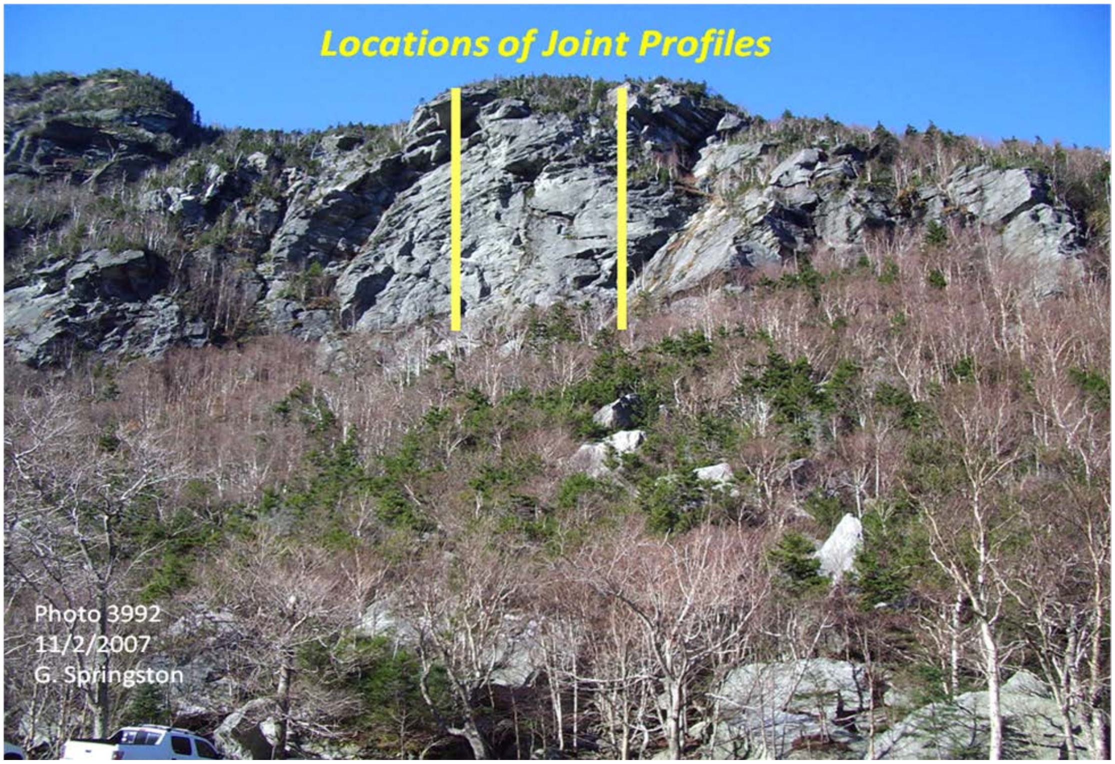


Figure 8.5. Location of study of joint spacing for J1 foliation-parallel joints on the northwestern cliffs. A frequency histogram of spacings is shown in Figure 8.6.

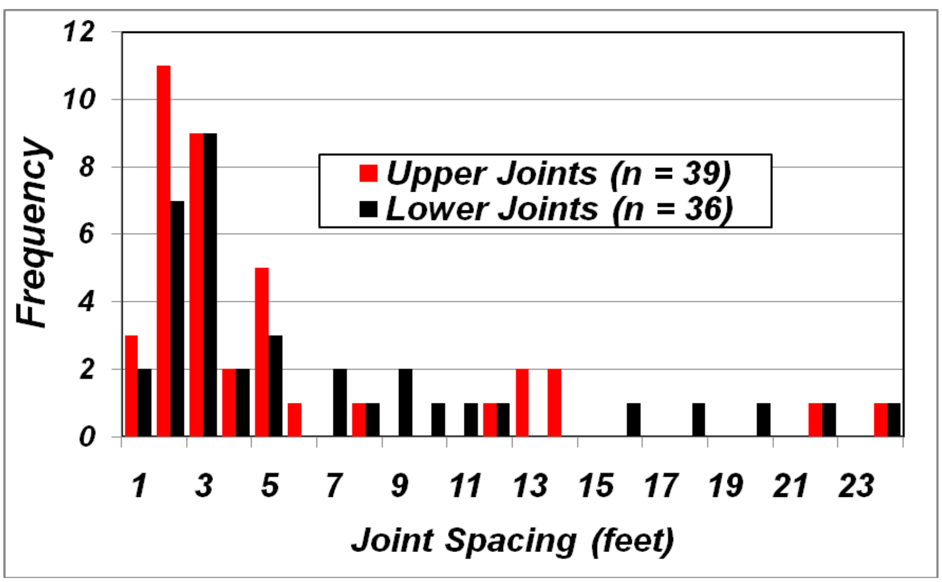


Figure 8.6. Spacing of J1 foliation-parallel joints on the northwestern cliffs. A composite of two profiles shown in Figure 8.5. Red bars indicate the number of joint spacings in the upper sections of the two profiles and black bars indicate spacings in the lower sections of the profiles. There appears to be no significant difference in joint spacing between the upper and the lower sections.

As outlined in Chapter 5, the development of the joint sets described above leads to several types of rock slope failures. Falls occur where a block detaches from an overhanging roof or breaks free from an overhanging wall. Topples occur when blocks are forced outward to such an extent that their center of gravity pulls them out and over. Slides and wedges occur when restraining blocks are moved, the coefficient of friction on one or more sliding surfaces is reduced, or some other force comes into play to increase pressure out and away from the rock mass. The long-term causes and ultimate triggers of these rock slope failures are discussed in the next chapter.

Christman (1959) discerned a shallow synform in the dominant foliation in the crest of the Anticlinorium in Smugglers Notch. Although field observations showed that some sites did indeed have shallow dips in the foliation towards the center, others both field observations and stereonet analysis by sector suggests that this is not a strong pattern. To the extent that this does occur, it is likely to add to the likelihood of toppling failures.

The height and steepness of the cliffs is at least partially the result of the fracture geometry described above. Cliffs on both sides of the Notch have their shape as viewed from above controlled by tall, faces developed alternately on the J2 and J3 joints. On both sides, the gullies or rock chutes that cut deep into the mountainsides seem to develop more on the J3 set than the J2 set. The causes of rock slope failures in the study area, as well as those that result in debris flows, are discussed in the next chapter.

9. Slope Failure Processes

> *It is quite evident that those huge bowlders fell from the adjacent ledges, and, in some cases, their downward course is traced upon the slope of land beneath the cliffs, and their length of leap is given by the distance between the deep indented holes along the path.*
>
> Hitchcock and others, 1861, p. 881

This chapter will discuss some of the processes that lead to rock falls and debris flows in Smugglers Notch. The monthly distribution of landslides in the Mount Mansfield area will be compared to that in New Hampshire. The debris flows at Smugglers Notch are closely associated with intense rainstorms and/or rapid snowmelt and examples will be described of meteorological triggers of two rock fall events and two debris flow events in Smugglers Notch. This is followed by an analysis of the amount and frequency of precipitation at Mount Mansfield and a discussion of the use of precipitation thresholds. Finally, the processes operating to break down the cliffs will be summarized and illustrated in Figure 9.10.

Water is a very important cause of rock slope instability (Wieczorek, 1996). This can come about by several mechanisms. First, water pressure in a fracture can reduce the normal stress on the fracture and lead to slip. Second, water in near-vertical fractures can increase the force driving a block outward from a face. Third, the alternate freezing and thawing of water in a fracture or saturated soil that fills a fracture may expand the fracture. Finally, the freezing of water out on the face can lead to increased pore pressure of water trapped behind the ice. This would thus reduce the normal stress on the fracture as described in the first case above.

The general recognition of the importance of water is confirmed by the USGS study of rock mass displacement at Smugglers Notch (Lee and others, 1994, 1997.) This concluded that incremental movements due to freeze-thaw cycling were an important mechanism in making the cliffs more susceptible to slope failure.

When the dependence of debris flow activity on intense precipitation or rapid snowmelt is taken into consideration, it is clear that water plays a critical role in most of the slope instability issues at Smugglers Notch.

However, there are many other potential causes of landslide activity. Besides the water-related facors described above, intense vibrations such as those from earthquakes can be important triggers for landslides (Cruden and Varnes, 1996). Regression analyses have been undertaken to relate landslide occurrence to earthquake magnitude and epicentral distance (Sidle and Ochiai, 2006, Chapter 5), but it is not clear that these are particularly applicable to Vermont conditions. It does appear likely, however, that only a relatively large earthquake would induce significant landslides at Smugglers Notch. At present, there is no known correlation of a landslide at Smugglers notch with an earthquake

Timing of Landslides

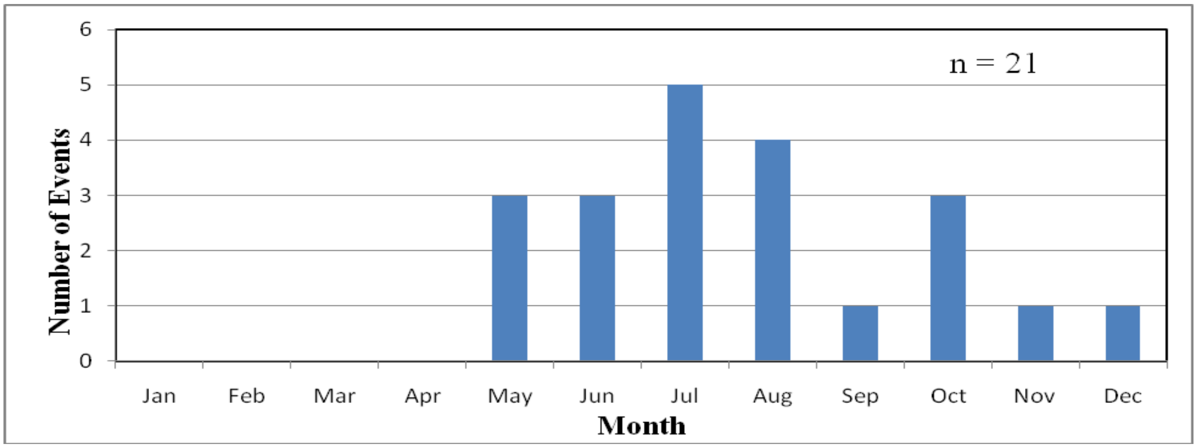
Landslides in the Notch and on Mt. Mansfield have occurred in each of the months from May through December. Figure 9.1 is a pair of histograms showing the month of occurrence for landslides in the Smugglers Notch/Mount Mansfield area compared with data for the White Mountains of New Hampshire (Flaccus, 1958 and Milender, 2004.) Figure 9.1A includes 21 Smugglers Notch and vicinity events for which the month of occurrence could be determined, out of a total of 28 natural events listed in Table 7.1. Note that this figure tallies days on which landslides occurred. A day with multiple events, such as May 22, 1986, when 12 debris flow events occurred in the Notch (Lee and others, 1994), counts as one day by this method.
Although the figure shows the peak frequency in July, the number of dated events is quite limited. As will be discussed in the Chapter on causes, these landslides can occur during any month where heavy snowmelt or rainfall can occur.

The single event listed for December is the report of the fall of King Rock in December of 1910. Other reports would put this event in the spring of 1910 or the spring of 1911, which would be more in keeping with the usual pattern, but research by Wendy Parrish of the Stowe Historical Society suggests that “about” December, 1910 is the most likely time for the rock fall (February 28, 2008 email communication from Wendy Parrish.)

The distribution of debris avalanche events in the White Mountains of New Hampshire is shown for comparison in Figure 9.1B. This too, shows days on which landslide events occurred. In the New Hampshire study by Flaccus (1958), 127 slides out of a total of 270 were dated to the month. To this was added the 1959 debris avalanche in Franconia Notch described by Milender (2004.) Many of the White Mountain landslides occurred in groups during heavy rainfall events. Thus, these events occurred on 19 different days spanning the warm months from June through November. It is somewhat surprising that no May events are listed in the New Hampshire catalog, but it should be remembered that many of the 270 or more events were not dated.

Table 9.1 on the following page compares monthly debris flow activity with rock fall activity. Note that they are very similar. This is probably because although the debris flows require heavy rainfall for initiation, the rock falls too are made more likely at times of abundant rainfall. See the discussions of meteorological conditions below.

A.



B.

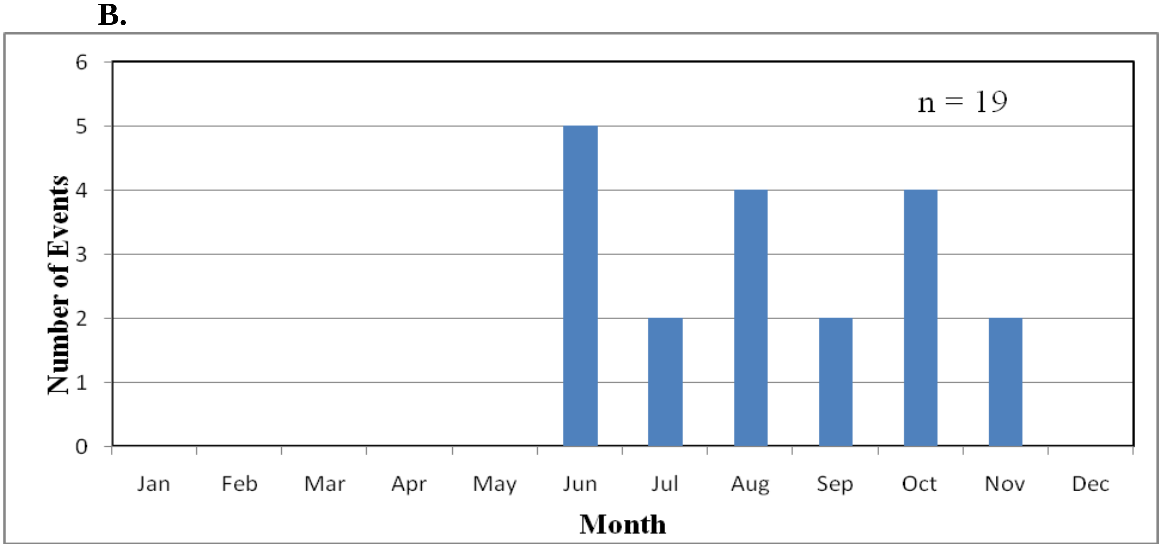


Figure 9.1. Monthly frequency of rock fall and debris flow/avalanche events. A) Number of days with rock fall and debris flow events at Smugglers Notch and Mount Mansfield for which month of occurrence is known. Data from Table 7.1. The apparent summer peak in activity is consistent with observations by the District staff of the VAOT (Tim Wilson, personal communication, January, 2008.) B) Frequency of debris avalanches in the White Mountains of New Hampshire. Although November debris avalanche days are relatively uncommon in New Hampshire, the two days on record were during the tremendous rainstorms of November 3 and 4, 1927, which resulted in about 21 debris avalanches in the White Mountains. Data for the White Mountains modified from Flaccus (1958) by addition of the October 24, 1959 debris avalanche in Franconia Notch (Milender, 2004.)

Table 9.1. Comparison of monthly frequency of debris flows and of rock falls/slides. Sources as described in Table 7.1. Events involving both debris flow and the apparent fall or slide of rock from the cliffs are tallied in both columns.

Month	Rock fall or slide	Debris flow
January	0	0
February	0	0
March	0	0
April	0	0
May	2	4
June	0	3
July	3	1
August	1	4
September	1	0
October	3	0
November	0	1
December	1	0

Meteorological Conditions at Times of Slope Failure

The figures below emphasize the connection of slope failures in the Notch with heavy rainfall. This is the basis for the recommendation that real-time monitoring of rainfall events can be used to provide warnings of an increased likelihood of slope failures. Figure 9.2 shows the general precipitation and snow depth data for 2006 and the times of three landslide events. The June event is shown in more detail in Figure 9.3, the August event in Figure 9.4, and the November event in Figure 9.5.

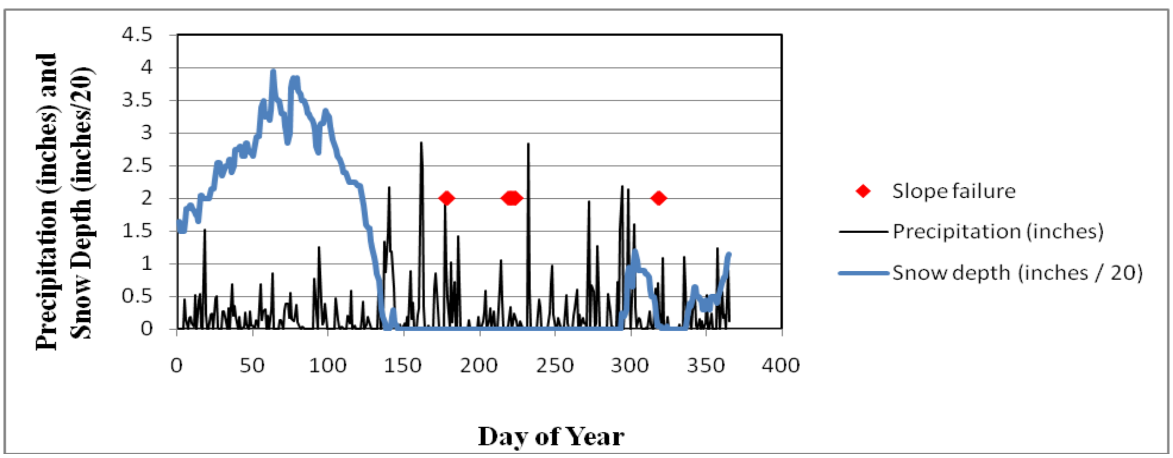


Figure 9.2. Precipitation and snow depth for year 2006 with times of slope failures. The slope failure events shown occurred on June 27 to 28, somewhere between August 3 and 12, and November 14 to 15. As will be shown in the figures below, the June and November events correspond well with the rainfall peaks. The timing on the August rock fall event is too loose for a definite correlation to be made. Note that the November event occurred during a time of both

heavy rainfall and snowmelt. Data is based on daily precipitation totals from NOAA Cooperative Station 435416 (Mt. Mansfield.)

The debris flow event at Hidden Gully was described in some detail in Chapter 7. Figure 9.3 shows that there was heavy antecedent precipitation, which would have served to saturate the soil prior to June 27. Further heavy rainfall on or about June 27 or 28 led to the debris flow event.

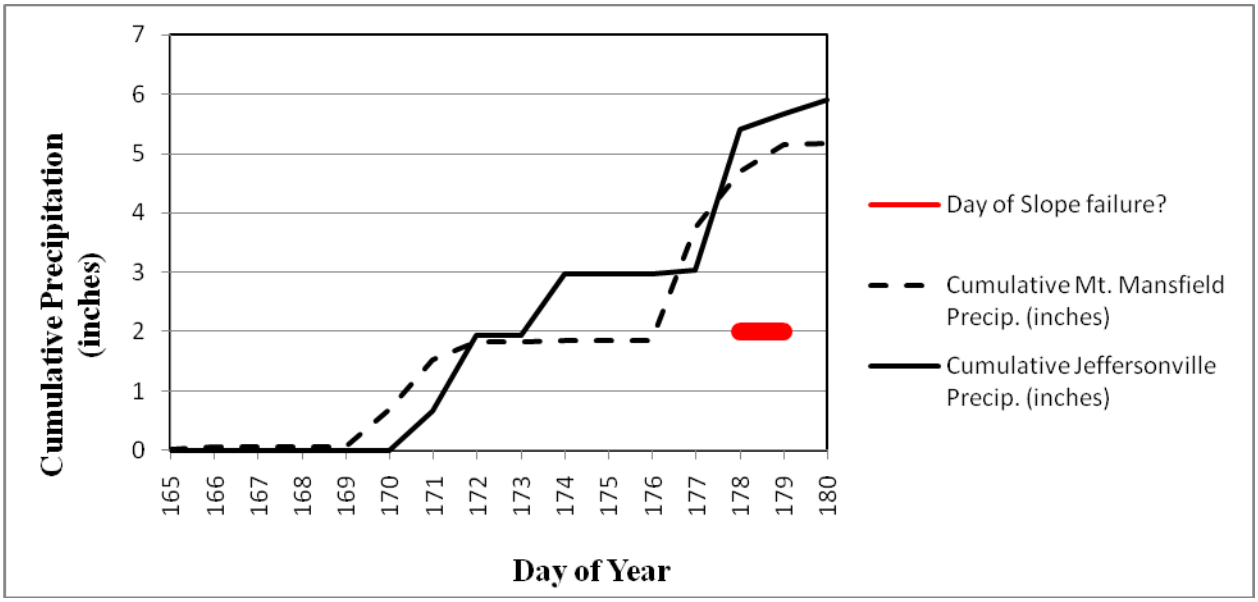


Figure 9.3. Cumulative precipitation prior to the debris flow event below Hidden Gully, June 27 or 28, 2006 (Day of year = 178 to 179.) Data is based on daily precipitation totals from NOAA Cooperative Stations 435416 (Mt. Mansfield) and 434261 (Jeffersonville, Smugglers Notch WTP.) For understanding the timing of precipitation it is important to understand that the Mount Mansfield station reports in the afternoon while the Jeffersonville station reports each morning. Thus, the Mt. Mansfield station will report precipitation that fell over the morning and early afternoon hours a day prior to the Jeffersonville station. Thus, an offset is introduced between the two stations.

Of the several important possible causes of slope instability, high pore pressure in soil or fractures due to precipitation or snowmelt is perhaps the most often cited factor. In the case of the Easy Gully rock fall of August, 2006, we know that this was an exceptionally wet summer, with July precipitation at the Morrisville Airport totaling 5.09 inches and rainfall for the first part of August totaling 1.9 inches through the 10th. The peak rainfall in early August occurred on the 2nd, when 1.33 inches fell. As described in Chapter 7, the rock fall occurred between about August 3 to 12.

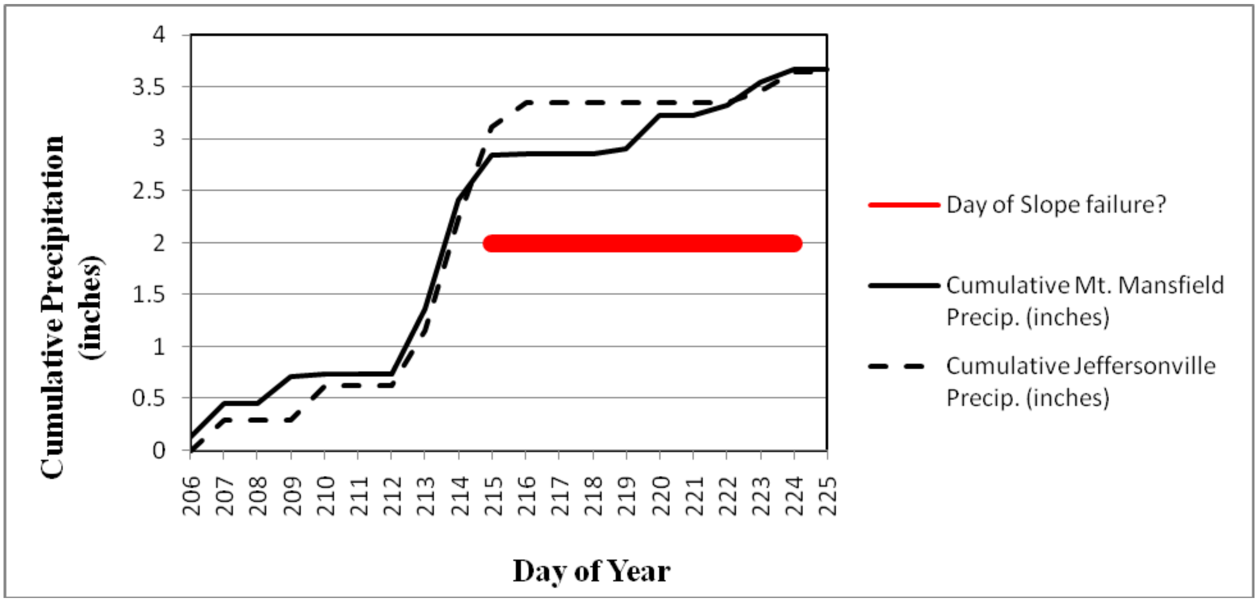


Figure 9.4. Cumulative precipitation prior to the rock fall event at Easy Gully, early August, 2006 (August 3 to 12, Day of Year = 216 to 224.) The timing of this slope failure is not tightly constrained so it is difficult to tell whether or not it was directly the result of the heavy precipitation on August 1 to 3 (Day of Year = 212 to 213.) The slope failure could well have occurred a day or two earlier than shown.

Precipitation and snowmelt that preceded the minor debris flow event of November 14 or 15, 2006 are shown in Figure 9.5. This event is described in detail in Chapter 7. Note that snow had come to the mountain earlier in the month but had been melting for several days prior to the debris flow event. Precipitation in the days prior to the debris flow was in the form of rain rather than snow.

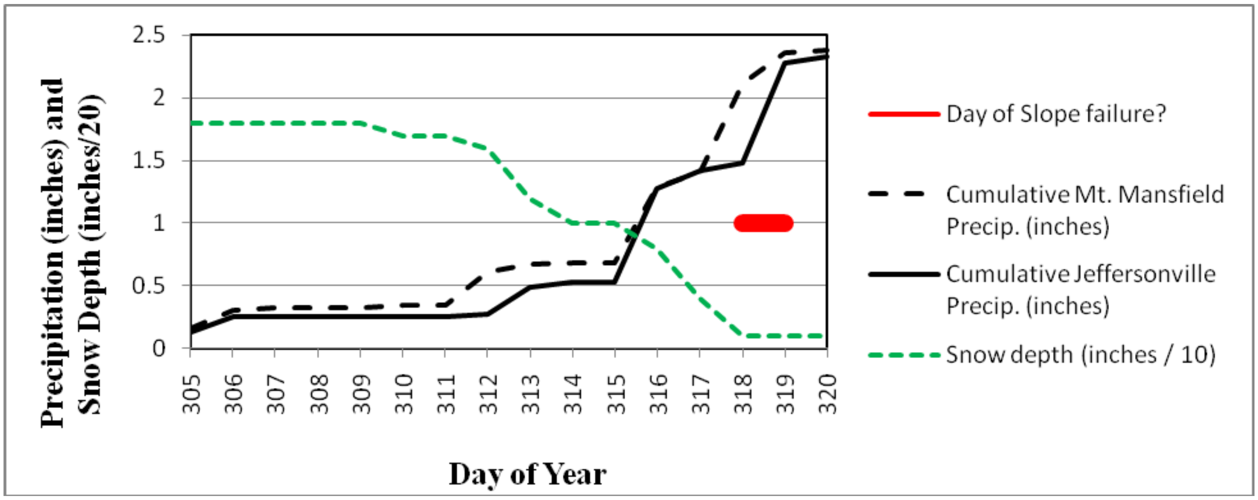


Figure 9.5. Cumulative precipitation and snow depth prior to the minor debris flow events on the west slope of Smugglers Notch on or about November 14 or 15, 2006 (Day of Year = 318 to 319.) Snow depth is for the Mount Mansfield station. Note that there had been considerable precipitation in the preceding days. As indicated in this figure, temperatures were generally above freezing and the snow depth at the top of the mountain had been declining for several days prior to the slope failure.

A clear case of the connection between precipitation and a rock block slide event is shown in Figure 9.6. On November 21, 2007, two large blocks of ledge and associated debris detached and slid down a steep slope out onto Route 108, causing the road to be closed until the material could be removed. This rock block slide is described in Chapter 7. The probable cause of movement of the blocks was increased pore pressure in fractures behind and/or under them.

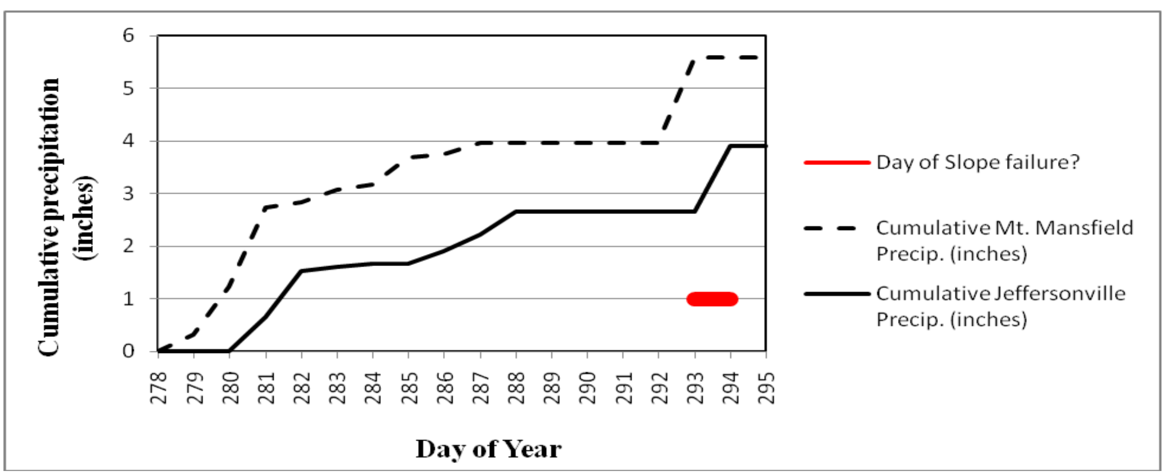


Figure 9.6. Cumulative daily precipitation prior to the rock slide of October 21, 2007 (Day of Year = 294.) The report from the Agency of Transportation is that the slide occurred early on the morning of the 21st. The Day of Slide line is shown extending back to Day of Year 293 simply to accentuate the line.

Mount Mansfield Climatology

The closest meteorological station to the study area is located at the summit of Mount Mansfield. Although the station is located at a higher elevation than the Notch (3950 feet or 1204 meters at the Mount Mansfield Station versus 2100 feet or 640 meters at the floor of the Notch), the climate data from this station is likely to be more representative of the climate in the Notch than any of the other available stations, which are all at relatively low elevations. Data from this station is summarized in Table 9.2 and Figures 9.7 to 9.9 below. On average, the highest precipitation occurs in the months June through November Table 9.2 and Figure 9.7). This corresponds well with the landslide frequency data in Figure 9.1. The mean temperature does not reach 32°F until April and drops below this level by November. The mean monthly low temperature is only above 32°F from May through September.

Table 9.2. Climatological data for NOAA Cooperative Station 435416 (Mt. Mansfield.) Averages are for the period 1971-2000. Annual totals may be slightly different than monthly totals due to rounding. Temperatures are reported in Fahrenheit and rainfall/snowfall totals are reported in inches. Downloaded from http://www.erh.noaa.gov/btv/climo/mt_mansfield.shtml on 3/9/2009.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average High Temperature	18	20	28	39	54	62	66	64	56	45	33	23	42
Average Low Temperature	1	4	13	24	38	47	52	50	42	31	20	7	27
Average Mean Temp.	10	12	20	32	46	54	59	57	49	38	26	15	35
Record High Temperature	50	51	64	74	79	84	82	79	78	71	63	60	84
Record Low Temperature	-39	-36	-29	-13	5	20	24	25	16	-5	-15	-40	-40
Average Days > 90 Deg.	0	0	0	0	0	0	0	0	0	0	0	0	0
Average Days < 32 Deg.	31	28	29	24	10	1	0	0	5	18	27	31	204
Average Days < 0 Deg.	15	12	6	0	0	0	0	0	0	0	1	9	43
Average Rainfall	**5.9**	**4.5**	**5.9**	**6.3**	**6.2**	**6.9**	**7.5**	**8**	**7.6**	**6.4**	**7.4**	**6.4**	**78.8**
Record Rainfall	11	9.1	9.9	18	12	15	13	13	19	13	12	13	92.88
Average No. of Rain Days	22	16	17	15	15	16	16	16	16	14	19	21	203
Average Snowfall	46	37	40	25	3.6	0.1	T	0	0.4	8.6	38	45	243
Record Snowfall	78	69	78	50	27	4	T	0.2	4	27	69	91	332.1
Average No. of Snow Days	18	14	13	7	2	0	0	0	0	4	11	17	86

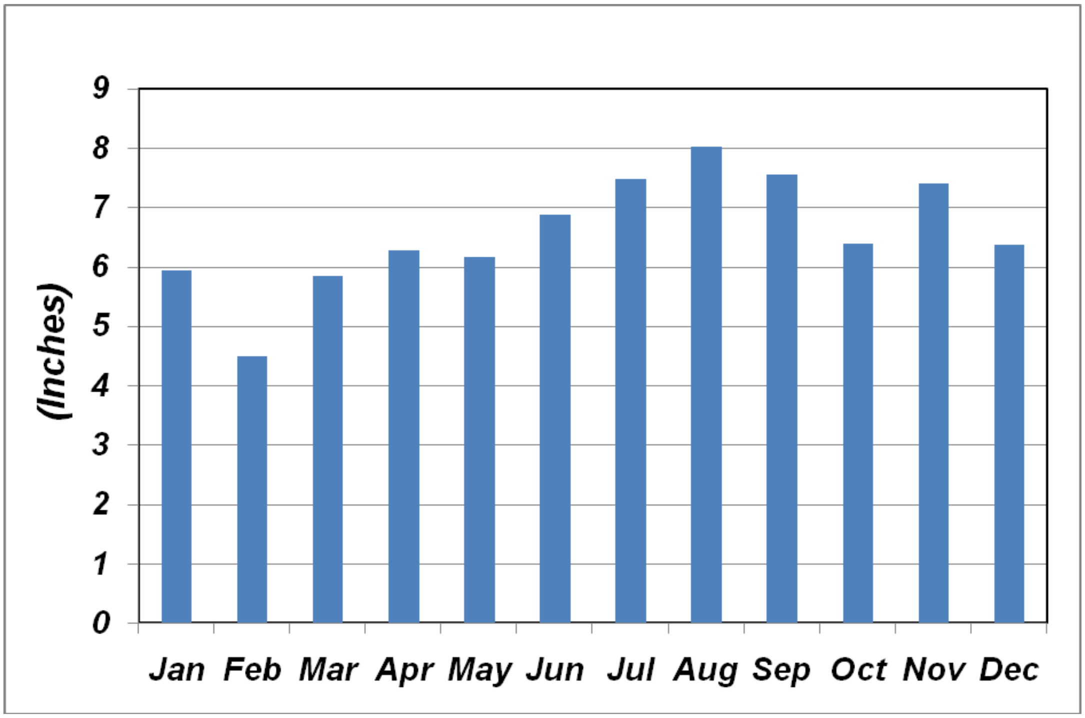


Figure 9.7. Mean monthly precipitation at Mount Mansfield, 1971-2000. Data is from NOAA Cooperative Station 435416 (Mt. Mansfield.)

Maximum annual 24-hour precipitation for the Mount Mansfield station is shown in Figures 9.8 and 9.9. Figure 9.8 shows the data in two forms: the annual maximum and the maximum for the months of May through October of each year. Almost all of the maxima occurred in these months. As described below, the 1999 peak is so anomalously high it is interpreted to be an event of a much longer recurrence interval than the period of record (53 years.) Figure 9.9 is a plot of recurrence interval versus maximum annual precipitation. This shows the likelihood of 24-hour precipitation of a given amount and clearly shows that 24–hour storms of 2 to 3 inches magnitude are relatively common. This strongly suggests that the debris flow events described in the preceding section can be expected to recur frequently. This is consistent with the analysis of triggering conditions for New Hampshire debris avalanches of Milender (2004), that are described at the end of this chapter.

Partial confirmation that this level of rainfall is sufficient to induce landslides comes from Baskerville and others (1988, p. 8) who report that Mr. Edward Salvas, an employee of WCAX-TV (the operators of antenna facilities on Mount Mansfield and are also the NOAA Cooperative Observers) stated "…that rainfall of 3 in (8 cm) or more commonly triggers mud and rock slides of varying proportions on the mountain."

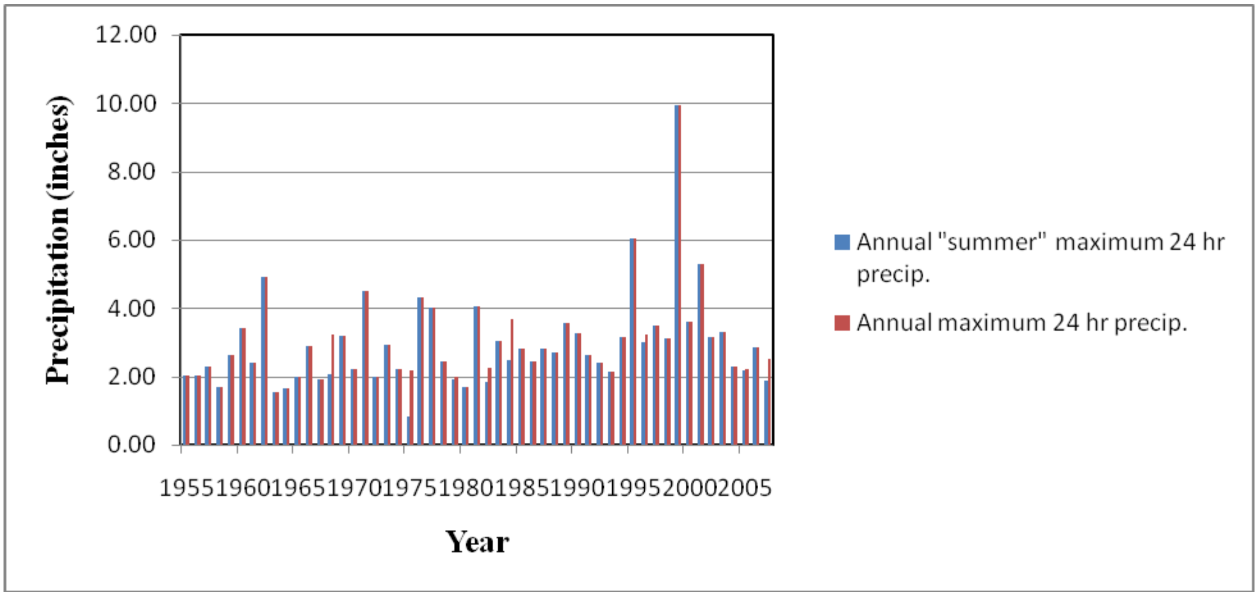


Figure 9.8. Maximum annual 24-hour precipitation at Mount Mansfield for 1955 to 2007. The annual mximum is the highest 24-hour total reported for each year. The "summer" maximum is the highest for May through October. Note that for most years the maximum falls during May through October. Data is from NOAA Cooperative Station 435416 (Mt. Mansfield.)

The data from the Mount Mansfield station is a useful beginning to understanding the meteorological triggers of landslide activity in the study area. However, it is less than ideal in that the precipitation data is only recorded on a daily basis. In order to fully understand the precipitation question, information is needed on the amount of precipitation, the intensity of the rainfall, and the frequency of occurrence or recurrence interval. The analysis of the Mount Mansfield data can only be done in terms of amount of precipitation in 24 hours or multiples of 24 hours. Data is actually needed from recording rain gages, which would supply data on shorter time intervals such as 30 minutes, 1 hour, etc.

Thresholds for Debris Flow Activity

Just this sort of data on the amount, intensity, and frequency of precipitation has been used to develop thresholds for debris avalanche activity in New Hampshire. In a study of debris avalanche activity in the White Mountains of New Hampshire, Milender (2004) proposes a two-part threshold:

1. Storm delivering 2 inches in 24 hours with peak intensity of 0.7 inches/hour or greater

2. Storm delivering 2.5 inches or more over 30 hours.

The first threshold is for a very intense storm of short duration, while the second is for cases of storms of longer duration that are not as intense. Although climatic and geologic conditions are not identical in the Smugglers Notch area, these thresholds appear to be reasonable starting points for predicting times of debris flow hazard in the Smugglers Notch area. These thresholds are also broadly consistent with the observations of Mr. Edward Salvas of WCAX-TV on triggering levels that were cited on page 62 of this report (3 inches or more).

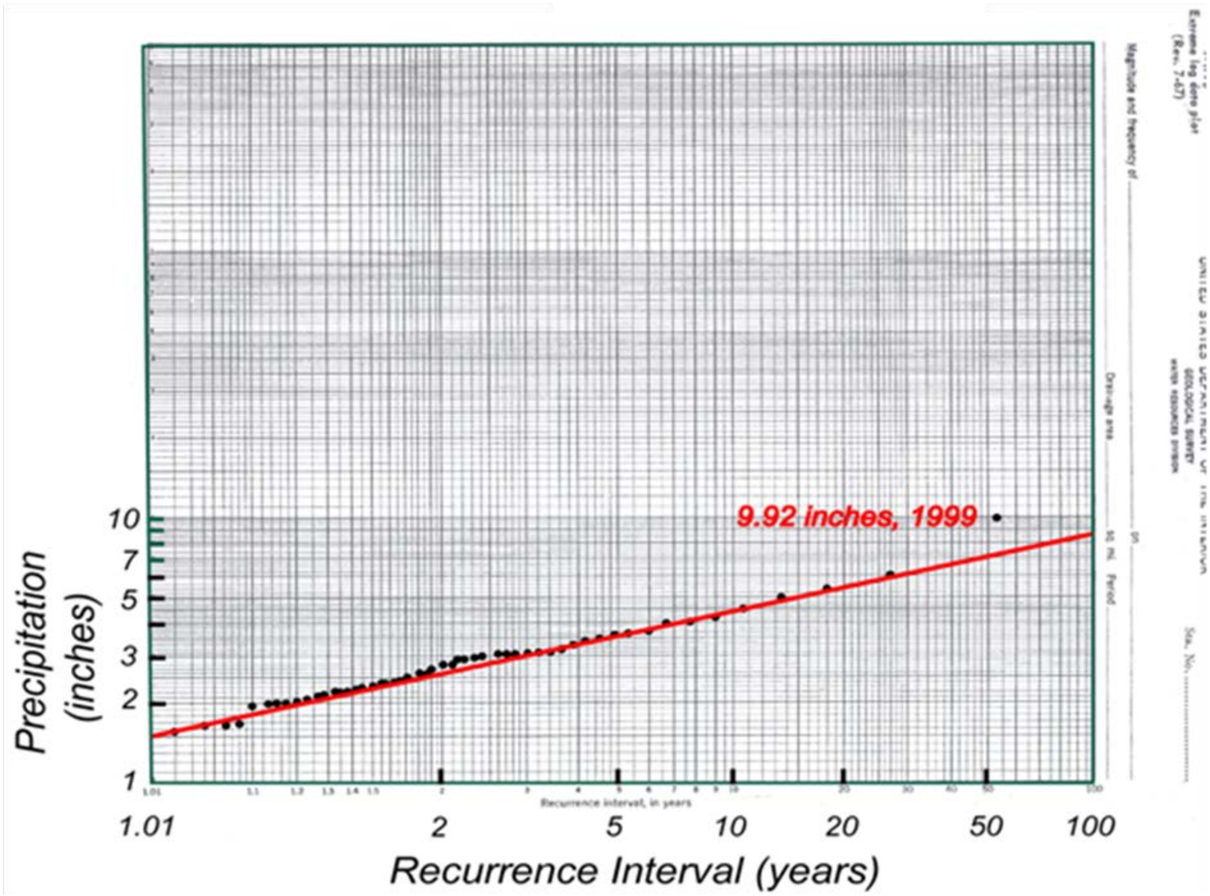


Figure 9.9. Recurrence interval of peak annual 24-hour precipitation at Mount Mansfield, 1955 to 2007. Data is from NOAA Cooperative Station 435416 (Mt. Mansfield.) Annual maxima were plotted using a log-Gumbel extreme value distribution (USGS Form 9-179b.) The 1999 peak is viewed as anomalous due to the poor fit when compared with all of the other values. Regardless of the interpretation of the 1999 peak, this plot demonstrates that storms exceeding two to three inches within 24 hours are relatively common in the vicinity.

Active Slope Degradation Processes
A summary of the active slope degradation processes that operate at Smugglers Notch is given in Figure 9.10. The orientation of individual faces on the cliffs is largely controlled by the steep J2 and J3 joints. Weathering processes weaken exposed rock on the outer faces of the cliffs and in the rock chutes. Thus, rock fall can occur from any location on the cliffs. This process has, in the past built up the large talus deposits and is still quite active today. Debris flows, by contrast, appear to originate below rock chutes, which, besides serving as source areas for rock debris (Figure 9.11), serve to focus stormwater and/or rapid snowmelt from catchments on and above the cliffs. Some of these debris flows may actually start out as debris slides, but by the time they reach the lower parts of the talus slopes and debris cones, the landforms and deposits indicate that they are rapidly moving slurries of debris.

The level of debris flow activity appears to be accentuated on the west side of the Notch due to the increased height of the mountain slopes on that side and the concave topography, the combination of which results in enlarged catchments for the rock chutes. By contrast, the east side of the Notch is lower and much of the east side has a convex topography, resulting in smaller catchments. Note, however that the largest recorded debris flow event occurred on the eastern side at the southernmost debris flow near the Stowe-Cambridge town line. This is not surprising as this feature has one of the larger catchments in the study area.

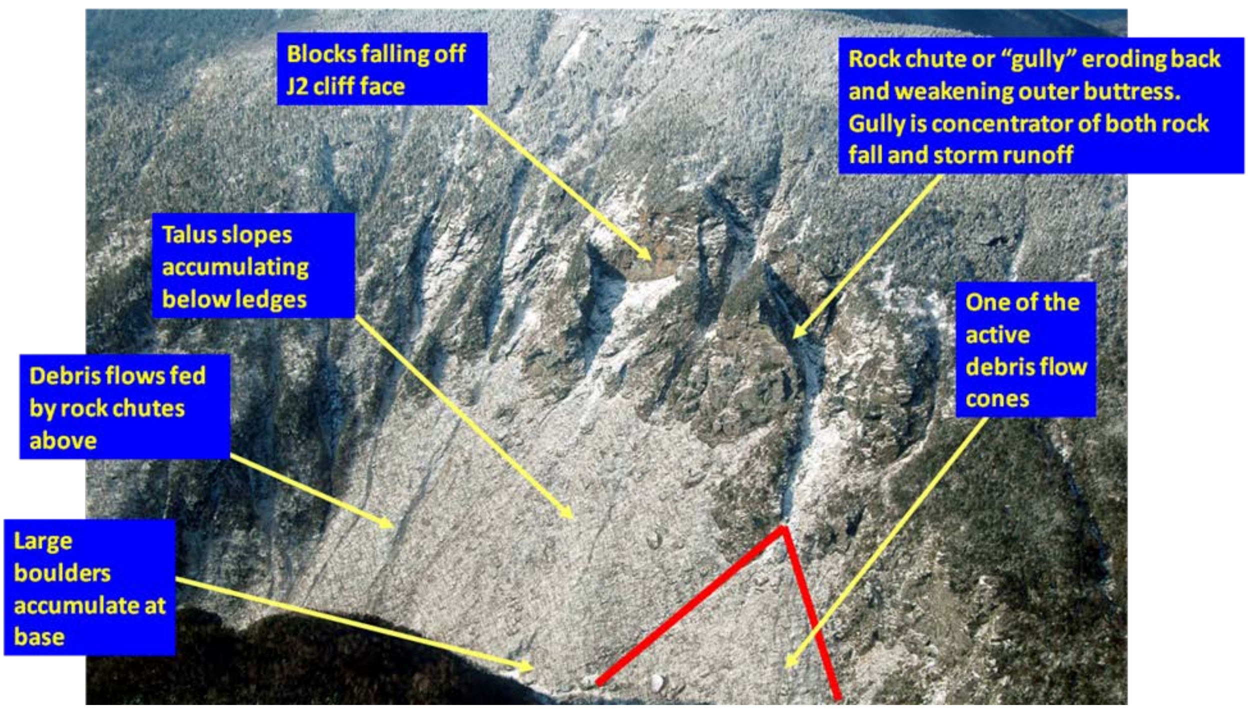


Figure 9.10. Summary of active slope degradation processes at Smugglers Notch. Aerial view of west side taken by Tom Eliassen, Fall, 2007. Weathering processes weaken exposed rock on the outer faces and in the rock chutes. Thus, rock fall can occur from any location on the cliffs. Debris flows, by contrast, appear to originate below rock chutes, which, besides serving as source areas for rock debris, serve to focus stormwater and/or rapid snowmelt from catchments on and above the cliffs.

Figure 9.11. Looking down Easy Gully in July, 2007. Note abundant debris in center of gully and heavy vegetation on cliffs. This material ultimately feeds down onto the Easy Gully debris flow cone. Photo by Marc Couper, Stowe Mountain Rescue Service.

10. Slope Instability Hazards

The field mapping, aerial photo interpretation, historical analysis, and structural analysis described in the preceding chapters were used to develop a map of slope instability hazards, which is shown in Figure 10.1 and Plate 5. This map delineates areas of high, moderate, and low hazard on the basis of evidence for continued and future rock fall and debris flow hazard. In addition, two areas of high fluvial erosion hazard (active alluvial fans) are shown. Except for the alluvial fans, hazards along stream due to fluvial erosion or inundation were not evaluated.

All of the areas of rock ledge shown in Figures 4.3 and 6.1 and on Plate 4 are considered to be areas of high hazard for rock fall. Every high section of rock ledge or cliff that was examined has multiple joint-bounded blocks, either on a face or in a gully, that are at long-term risk of falling, toppling, or sliding. Overhangs and loose blocks are common on all sections of the high cliffs.

The areas mapped as mountain slope, which make up the majority of the study area, are considered to be of moderate to low risk for rock fall or debris flow activity. These are generally to the side or above the major rock ledges described above and do not show evidence of debris flow activity. Exceptions may be the sections of mountain slope in the vicinity of the upper parts of the rock chutes and debris flows. There may well be high hazard of rock fall or debris flow in some parts of these upper slopes. However, these areas are quite distant from the areas of high human traffic and were for the most part not visited in this study. If the immediate vicinity of each of the upper rock chutes and debris flows is viewed as a high hazard area, then that should adequately portray the hazard in the mountain slope areas.

For the reasons outlined in Chapters 5 and 7, the debris flow channels and debris flow deposits need to be viewed as high hazard areas. Note that this high hazard designation must also include the channels mapped as "inactive" as this designation simply records that there has not been recent activity, not that no further activity can be expected. This is because channel blockages are common along debris flow paths and old channels can then become reactivated. Besides the channels themselves, the surrounding sections of talus are liable to have debris flows shift over onto them as channel blockages occur in the existing channels. The debris flow cones that have formed below Easy Gully, Hidden Gully, and Elephant's Head Gully have formed by just this process of shifting channels.

The large boulders that litter the floor of the Notch are strong evidence that rock fall hazards are high. Although the well-developed soil and vegetation on some indicate that they fell long ago, there is abundant evidence (as outlined in Chapter 7) that they continue to come down today.

Tom Eliassen of the Materials and Research Section of the VAOT ran a computer simulation using the program ROCFALL by Rocscience, Inc. to model the fall of boulders from the cliffs north of Easy Gully down towards Route 108. The results of this preliminary analysis are shown in Figure 10.2 and suggest that the boulders will have relatively low bounces, but it may be quite significant that all of the modeled boulder falls reached the bottom of the valley. Although the topographic data used in the model is not detailed enough to show all of the irregularities, and the effect of trees on the falling rocks is ignored, this does provide further evidence that many of the rocks that do fall will quite commonly reach the highway below.

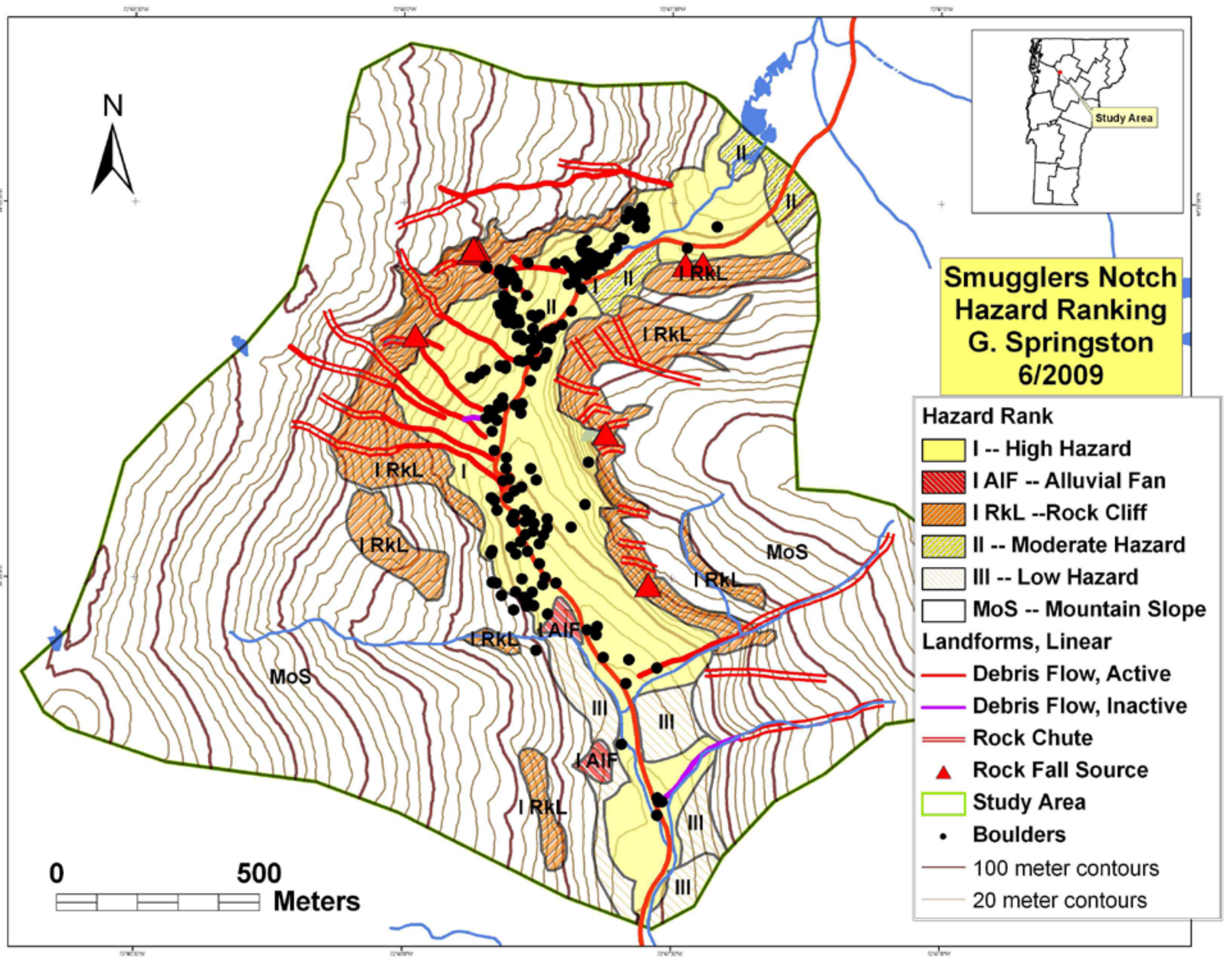


Figure 10.1. Slope instability map of the Smugglers Notch area. The high hazard area in the lower parts of the Notch is due to a combination of rock fall and debris flow hazards. The rock ledges or cliffs themselves are high hazard areas due to rock fall. The rock chutes and debris flow tracks extending above the cliffs are also high hazard areas. The alluvial fans are high hazard areas due to fluvial erosion hazards.

The extensive area in the floor of the Notch that is rated as high hazard is given that rating because of the hazards due to both debris flows and rock falls. As discussed in Chapter 9, the debris flow hazards have a strong correlation with intense rainfall events and/or possibly with rapid snowmelt events. The rock falls may not have such a strong tie, but are still more likely to happen in the hours and days following heavy rainfall events. Rock falls are probably also more likely to occur during or shortly after spring snowmelt, although the data at Smugglers Notch on springtime rock fall events is limited.

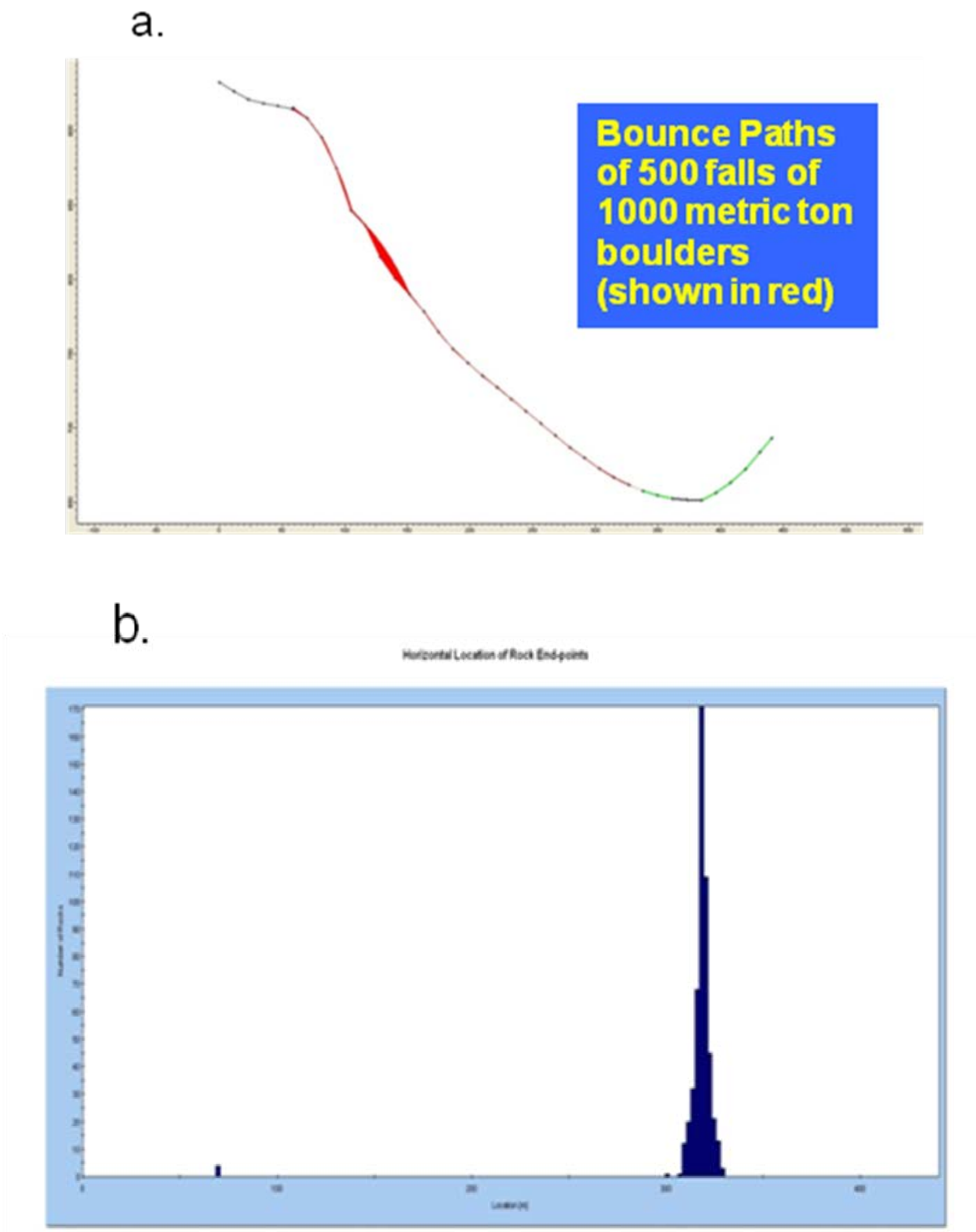


Figure 10.2. Monte Carlo simulation of rock falls from cliffs north of Easy Gully, Smugglers Notch. a.) Topographic profile with bounce paths of 500 falls of 1000 metric ton boulders (shown in red.) Note that the highway is at the bottom of the profile. b.) Histogram of rock bounce path endpoints. This diagram lines up with the one above. Note, therefore, that essentially all boulders reach the road at the valley bottom. Courtesy of Tom Eliassen, Materials and Research Division, VAOT.

11. Summary

Landslides, in the form of rock falls, rock slides, and debris flows have occurred in Smugglers Notch for thousands of years and we can expect large rock falls and slides and damaging debris flows to continue into the future.

The form of the cliffs is strongly controlled by three sets of fractures (joint sets) that intersect at near-right-angles to one another. One of the joint sets (J1) is sub-horizontal and the other two have very steep dips (J2 and J3). The outer faces of the cliffs on both sides of the Notch are composed of alternating J2 and J3 joint surfaces.

Two types of slope failures or landslides occur in the Smugglers Notch area: the first broad class of landslides is rock falls and rock slides, which involve one or many large pieces of rock detaching from a cliff and falling, bouncing, or sliding down a slope. Most of the boulders in the floor of the Notch appear to be the result of such rock falls. The second class of landslides includes the debris flows, which are slurries of water, mud, pebbles, cobbles, and boulders that flow within shifting channels on the talus slopes below the cliffs. In the Notch, they are caused by heavy rainstorms.

The rock falls can be expected to involve individual blocks well in excess of 500 or 1000 tons. The largest block to fall since records have been kept appears to be the 11,500 ton (10,400 metric ton) piece that broke off the west face north of Easy Gully on July 17, 1983.

The debris flows can be expected to range from a few cubic meters of mud, pebbles, cobbles, and boulders up to many thousands of cubic meters. The largest recorded debris flow descended from the east side on May 13, 1986 and consisted of about 327,000 cubic yards (250,000 cubic meters) of material. This blocked Route 108 and the West Branch at the site of the pull-off near the Cambridge-Stowe line. Future debris flows can also be expected to sweep down to and across Vt. Rt. 108.

Of 21 landslide events at Smugglers Notch and Mount Mansfield for which the month of occurrence can be determined, all occurred between May and December, with 19 of them occurring between May and October. The peak monthly occurrence is in July. Maintenance records from the Vermont Agency of Transportation suggest that there is also landslide activity that occurs prior to the opening of the road in May. This is most probably related to the spring thaw.

Only two eyewitness reports of landslides in Smugglers Notch are known. One involved a rockfall event and the other involved debris flows. In both cases, the witnesses fortunately escaped unharmed.

The history of landslides here at Smugglers Notch and Mount Mansfield, in the White Mountains of New Hampshire, and in many other regions shows a strong correlation between intense precipitation (and/or rapid snowmelt) and landslides. This correlation can be used to give some warning of times with an increased likelihood of landslide activity at the Notch. In a study of debris avalanche activity in the White Mountains of New Hampshire, Milender (2004) proposes a two-part threshold:

1. Storm delivering 2 inches in 24 hours with peak intensity of 0.7 inches/hour or greater

2. Storm delivering 2.5 inches or more over 30 hours.

The first threshold is for a very intense storm of short duration, while the second is for cases of storms of longer duration that are not as intense. Although climatic and geologic conditions are not identical in the Smugglers Notch area, these thresholds appear to be reasonable starting points for predicting times of debris flow hazard in the Smugglers Notch area. These thresholds are also broadly consistent with the observations of Mr. Edward Salvas of WCAX-TV on triggering levels that were cited on page 62 of this report (3 inches or more).

The landform maps show the areas of historic landslide activity. These landforms are largely the result of slope degradation processes and are described below. Weathering processes weaken exposed rock on the outer faces of the cliffs and in the rock chutes. Thus, rock fall can occur from any location on the cliffs. This process has, in the past built up the large talus deposits and is still quite active today. Debris flows, by contrast, appear to originate below rock chutes, which, besides serving as source areas for rock debris serve to focus stormwater and/or rapid snowmelt from catchments on and above the cliffs. Some of these debris flows may actually start out as debris slides, but by the time they reach the lower parts of the talus slopes and debris cones, the landforms and deposits indicate that they are rapidly moving slurries of debris.

The large boulders that litter the floor of the Notch are strong evidence that rock fall hazards are high. Although the well-developed soil and vegetation on some indicate that they fell long ago, there is abundant evidence (as outlined in Chapter 7) that they continue to come down today.

The level of debris flow activity appears to be accentuated on the west side of the Notch due to the increased height of the mountain slopes on that side and the concave topography, the combination of which results in enlarged catchments for the rock chutes. By contrast, the east side of the Notch is lower and much of the east side has a convex topography, resulting in smaller catchments. Note, however that the largest recorded debris flow event occurred on the eastern side at the southernmost debris flow near the Stowe-Cambridge town line. This is not surprising as this feature has one of the larger catchments in the study area.

The slope instability hazard map presents a relative ranking of areas of high and moderate hazard on the basis of evidence for continued and future rock fall and debris flow hazard. In addition, two areas of high fluvial erosion hazard (active alluvial fans) are shown.

12. Recommendations

These recommendations fall into two categories: management and monitoring. As documented in this report, there is sufficient information available to identify the high landslide hazard areas within the Notch. The months in which landslides are most frequent are reasonably well constrained. The relationship between heavy rainfall and landslide events in the Notch is well-established. However, in order to undertake effective management of the risk posed by landslides to the public, additional information is still needed.

Highway signs need to be moved down

The "Watch For Fallen Rocks" signs need to be moved down to the Cambridge/Stowe town line for traffic coming from the south and at least 1,500 feet north of the main parking lot for traffic coming from the north. Additional signs at the main parking lot and at Big Spring would be helpful, but these would be well within the higher hazard parts of the Notch.

Warning signs

Warning signs should be placed and maintained at trailheads and other access points for foot travelers.

Parking areas need to be reorganized

The informal parking area at the base of the Hidden Gully debris flow outlet should be closed off. This debris flow path seems to be particularly active and can be expected to disgorge large quantities of mud, pebbles, cobbles, and boulders during or after large rain events. At most this should be left as a spot where a single car can pull over to let others pass.

The areas of widened shoulder opposite the site of the October 21, 2007 rock slide (several hundred feet north of the main parking lot) should be rearranged to discourage parking of vehicles. Future slope failures are very likely in this vicinity.

Discourage any rogue camping at parking spots

I have not observed any camping taking place at the parking spots but, given the level of day use, at least occasional overnight tenting may be occurring. Campers sleeping in vehicles or tents at the pull-offs would be particularly vulnerable to rock fall or debris flow events occurring in the midst of a heavy rain storm.

Issue warnings based on real-time rain gage or weather radar

A recording rain gage with real-time telemetry should be established as close to the Notch as feasible. This should be located at a site with electric power so that it can function properly during times of snow and ice that occur even in the warmer months. Telemetry can be via land line, cell phone, radio, or satellite. One possibility would be to work with the U.S.G.S., who already have stream gaging stations on the West Branch of the Little River and Ranch Brook. They currently run a rain gage at the West Branch site, but it is not connected via telemetry. Alternatively, an arrangement could be made with one of the two ski areas.

As outlined in this report, we have a good idea of the amount of precipitation that is required to trigger slope failures. When precipitation amounts and/or rates exceed the threshold values described in this report, emergency personnel could be alerted and warnings could then be issued regarding slope failures. A cooperative arrangement involving the National Weather Service and other organizations such as the Vermont Emergency Management Agency and the VAOT is probably the most effective way to disseminate the resulting warnings.

Alternatively, the National Weather Service is developing a computer system to perform rapid flash flood hazard warnings. The system, called the Flash Flood Monitoring and Prediction (FFMP) combines radar information on precipitation intensity with accurate maps of small drainage basins and estimates of the amount of rainfall needed to produce flash flooding. The system is described on the National Weather Service website (http://www.nws.noaa.gov/mdl/ffmp/.) If applicable to the Smugglers Notch terrain and climate, this could be of great utility.

Near-real-time warnings based on precipitation, such as those described in the preceding three paragraphs, are likely to be the most effective actions that can be taken to reduce risk to the public from landslides at the Notch.

Include the Notch in statewide earthquake preparedness

Rainfall is not the only possible trigger for landslides in the Notch. As is well known, landslides can be triggered by earthquakes of sufficient magnitude. Thus, emergency planners should recognize that the possibility of rock falls in the Notch would be increased immediately following a substantial earthquake. This could result in a temporary closure of Vt. Rte. 108, thus blocking movement of vehicles between Stowe and Cambridge.

Continue landslide monitoring in the Notch

Monitoring of debris flow and rock fall/slide activity at the Notch should be continued. Information on the location, date, time, type of landslide, source area, volume of material, damage, and antecedent weather conditions should be recorded for each event. Observations during this study indicate that the debris flows cannot be expected to continue in their exact present locations; the debris flow paths are liable to shift over time as blockages occur.

For tracking of changes in the cliffs and talus slopes over time, it will also be important to build up a set of high-resolution images of the cliffs, taken from known stations. The photos should be taken in the spring prior to leaf-out but after snowmelt is largely completed (typically early May) and in the fall after the leaves are off the trees (October or early November.) Suggested locations for repeat photography are listed in Table 7.3.

13. Acknowledgements

Funding for this study was provided by the Vermont Department of Forests, Parks and Recreation and the Vermont Geological Survey, Department of Environmental Conservation, and the Vermont Agency of Transportation. Many thanks to Larry Becker, Vermont State Geologist, and Jonathan Wood (formerly Commissioner of the Department of Forests, Parks and Recreation and currently Secretary of the Vermont Agency of Natural Resources) for their ideas and encouragement. Jon Kim of the Vermont Geological Survey and Peter Thompson of the University of New Hampshire helped me understand the complexities of the bedrock geology. Marjorie Gale of the Vermont Geological Survey helped greatly with some GIS issues.

Neil Van Dyke, Marc Couper, Tim Burdick, Graham Govoni, and others from the Stowe Mountain Rescue Service provided invaluable first-hand information about the cliffs and gullies of the Notch and their various natural hazards. Marc shared a set of excellent photos with me. Tim and Graham expertly guided me up into Easy Gully and got me down safely.

Extensive discussions with Chris Benda and Tom Eliassen of the Materials and Research Section of the Vermont Agency of Transportation were of prime importance in understanding the natural hazards of the Notch and their implications. Tom kindly ran the rock fall simulation model shown in Chapter 10. He also shared many excellent photographs of the Notch and reviewed the manuscript.

Tim Wilson and the other staff at the Cambridge Garage of the Vermont Agency of Transportation supplied very helpful information on timing and locations of rock and debris damage to Vermont Rt. 108.

The successful completion of the photogrammetry study required the assistance of many individuals. Bob Getchel and the staff of the James W. Sewall Company produced the aerial photos and maps despite a much-delayed spring snowmelt. Many thanks to Scott Reeves from the Mount Mansfield Company, Steve Wry from Smugglers Notch Inc., Rick Paradis from the University of Vermont Natural Areas Program, and Ron Wells from the Vermont Department of Forests, Parks and Recreation for allowing placement of temporary targets on the lands under their management. The surveyors from the Vermont Agency of Transportation under the direction of Paul Hodge provided control point data for some very out-of-the-way spots.

Thanks also to the staff members and volunteers of the various libraries and archives: The Vermont Historical Society, Vermont State Archives, Vermont State Library, Special Collections at the Bailey-Howe Library of the University of Vermont, the Stowe Free Library, the Stowe Historical Society and the Kellogg-Hubbard Library. The online photograph collection of the Vermont Landscape Change Program of the University of Vermont was a great aid.

My wife Rose Paul read the manuscript and made many valuable suggestions.

14. References

Anonymous, 1911, October in the Cambridge Notch: Letters to an absent Vermonter, II: The Vermonter, v. 16, p. 21-26.

Baskerville, C.A., 1991, Styles of mass wasting in Vermont: Green Mountain Geologist: v. 18, no. 2, p. 4-5.

Baskerville, C.A., Ratte, C.A., and Lee, F. T., 1988, A rockfall and debris slide at Smugglers Notch, Mount Mansfield, Cambridge, Vermont: Vermont Geological Survey, Studies in Vermont Geology, No. 4, Waterbury, 10p.

Baskerville, C.A., Lee, F. T., and Ratte, C.A., 1993, Landslide Hazards in Vermont: U.S. Geological Survey Bulletin No. 2043, 23 p.

Bierman, P.R., Wright, S.F., and Nichols, Kyle, 1999 Slope stability and late Pleistocene/Holocene history, northwestern Vermont: *In* Wright, S.F., *ed.*, New England Intercollegiate Geologic Conference Guidebook No. 91, p. 17-50.

Bigelow, W.J., 1934, History of Stowe, Vermont (From 1763 to 1934): Published by the author, Stowe, 251 p.

Christman, R.A., 1956, The geology of the Mount Mansfield State Forest: Vermont Department of Forests and Parks, Montpelier, 27 p.

Christman, R.A., 1959, Geology of the Mount Mansfield quadrangle, Vermont: Vermont Geological Survey, Bulletin No. 12, Montpelier, 75 p. plus 3 plates.

Costa, J.E. 1998, Rheologic, geomorphic, and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows: *In* Baker, V.R., Kochel, R.C., and Patton, P.C., *eds.*, Flood geomorphology: John Wiley and Sons, New York, p. 113-122.

Cruden, D.M., and Varnes, D.J., 1996, Landslide types and processes: *In* Turner, A.K., and Schuster, R.L., III, *eds*., Landslides: Investigation and mitigation: Transportation Research Board Special Report 247, p. 36-75.

Eliassen, T.D., and Springston, G.E., 2007, Rockfall hazard rating of rock cuts on U.S. and State highways in Vermont: Vermont Agency of Transportation Report 2007-16, Federal Highway Administration Grant RSCH010-974, 31 p. plus appendix. http://www.aot.state.vt.us/matres/Documents/ACROBAT.pdf/S&FDox/AOT_RockfallHazardRatingSystemFinal2007.pdf

Flaccus, Edward, 1958, White Mountain landslides: Appalachia, v. 32, p. 175-191.

Flaccus, Edward, 1959, Revegetation of landslides in the White Mountains of New Hampshire: Ecology, v. 40, p. 692-703.

Fleming, R.W., and Varnes, D.J., 1991, Slope Movements: *In*, Kiersch, G.A., *ed.*, The heritage of engineering geology, The first hundred years: Geological Society of America, Centennial Special Volume 3, p. 201–218.

Hagerman, R.L., 1975, Mansfield: The story of Vermont's loftiest mountain: Phoenix Publishing, Canaan, New Hampshire, second edition, 120 p.

Hemenway, A.M., 1871, The Vermont Historical Gazetteer, v. 2, published by the author, Burlington, 1200p.

Hitchcock, Edward, Hitchcock, E., Jr., Hagar, A.D., and Hitchcock, C.H., 1861, Geology of Vermont: Claremont Manufacturing Company, Claremont, N.H., 2 volumes, 988 p.
Hungr, Oldrich, Evans, S.G., Bovis, M.J., and Hutchinson, J.N., 2001, A review of the classification of landslides of the flow type: Environmental and Engineering Geoscience: v. 7, p. 221-238.

Jacobs, E.C., 1938, The geology of the Green Mountains of northern Vermont: Vermont State Geologist, 21st Report, Montpelier, p. 1-73.

Kull, C.A., and Magilligan, F.J., 1994, Controls over landslide distribution in the White Mountains, New Hampshire: Physical Geography, v. 15, p. 325-341.

Lamoille County Regional Planning Commission, 1995, Smugglers Notch Scenic Highway corridor management plan: Report submitted to the Vermont Agency of Transportation, Montpelier,

Lee, F.T., Odum, J. K., and Lee, J.D., 1994, Rockfalls and debris avalanches in the Smugglers Notch area, Vermont: U.S. Geological Survey Bulletin 2075, 33p.

Lee, F.T., Odum, J. K., and Lee, J.D., 1997, Slope failures in northern Vermont: Environmental and Engineering Geoscience, v. 3, p. 161-182.

Milender, K.W., 2004, Debris avalanche hazards in Franconia Notch, New Hampshire: Unpublished thesis, Master of Science in Civil Engineering, University of New Hampshire, Durham, 288p.

Pierson, L.A., Davis, S.A., and Van Vickle, R., 1993, Rockfall hazard rating system: Participant's manual: Federal Highway Administration, U.S. Department of Transportation, 104 p.

Sidle, R.C., and Ochiai, Hirotaka, 2006, Landslides: Processes, prediction, and land use: American Geophysical Union, Water Resources Monograph 18, Washington, 312 p.

Stewart, D.P., (1961), The glacial geology of Vermont: Vermont Geological Survey, Bulletin No. 19, Montpelier, 124 p.

Stewart, D.P., and MacClintock, Paul, 1970, The surficial geology and Pleistocene history of Vermont: Vermont Geological Survey, Bulletin No. 31, Montpelier, 251 p.

Thompson, E.H. and Sorenson, E.R., 2005, Wetland, woodland, wildland: A guide to the natural communities of Vermont: University Press of New England, Lebanon, New Hampshire, 456 p.

Thompson, P.J. and Thompson, T.B., 1999, Digital bedrock geologic map of the Mt. Mansfield quadrangle, Vermont: Vermont Geological Survey, Open-File Report VG99-3, Waterbury, 3 plates, scale 1:24000.

Traffic Research Unit, 2009, 2008 (Route Log) AADTs: State Highways: Vermont Agency of Transportation, Montpelier, 71 p.

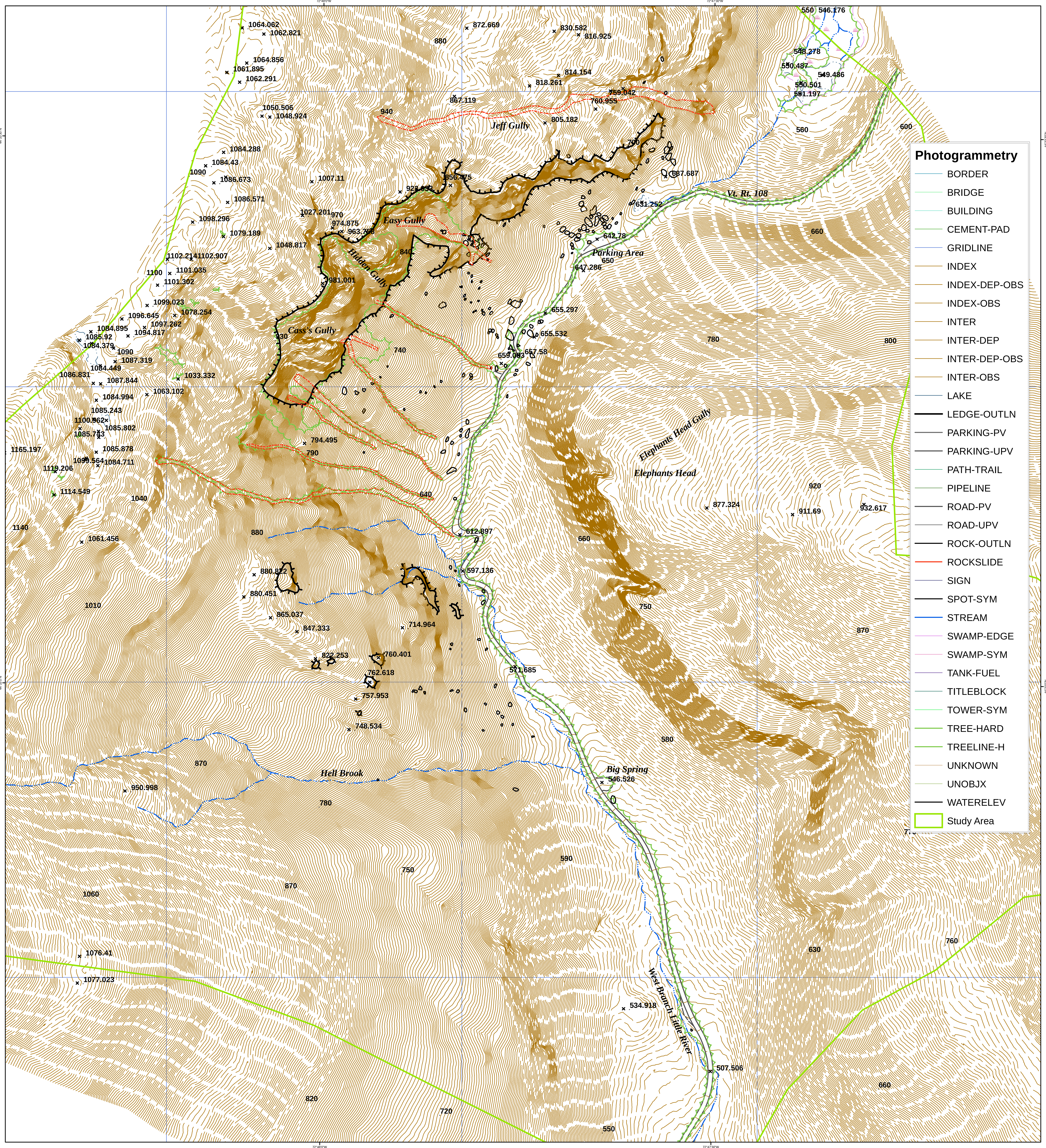
VanDine, D.F., 1985, Debris flows and debris torrents of the Southern Canadian Cordillera: Canadian Geotechnical Journal, v. 22, p. 44-67.

Varnes, D.J., 1978, Slope movement types and processes: *In* Schuster, R.L., and Krizek, R.J., *eds.*, Landslides: Analysis and Control: Transportation Research Board Special Report 176, p. 11-33.

Vermont Department of Forests, Parks and Recreation, 2002, Long Range Management Plan, Mount Mansfield State Forest: Agency of Natural Resources, Waterbury, 69 p. plus appendices.

Wieczorek, G.F., 1996, Landslide triggering mechanisms: *In* Turner, A.K., and Schuster, R.L., III, *eds*., Landslides: Investigation and mitigation: Transportation Research Board Special Report 247, p. 36-75.

Wright, S.F., 2003, Surficial geology of the Jeffersonville 7.5-minute quadrangle, northern Vermont: Final Report: Manuscript report submitted to the Vermont Geological Survey, 58 p.



Scale 1:2,500

0 500 1,000 1,500 Feet

0 100 200 300 400 500 Meters

Topography by photogrammetric methods by James W. Sewall Co. from aerial photos taken in May, 2007.

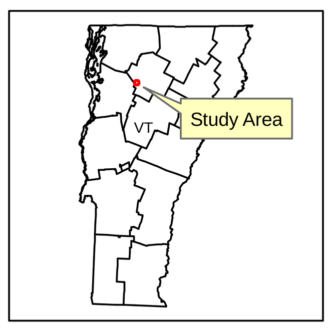
Contour Interval 2 meters.

Map produced for Vermont Geological Survey by Norwich University Geology and Environmental Science Department. Cartography by George Springston, March 25, 2008.

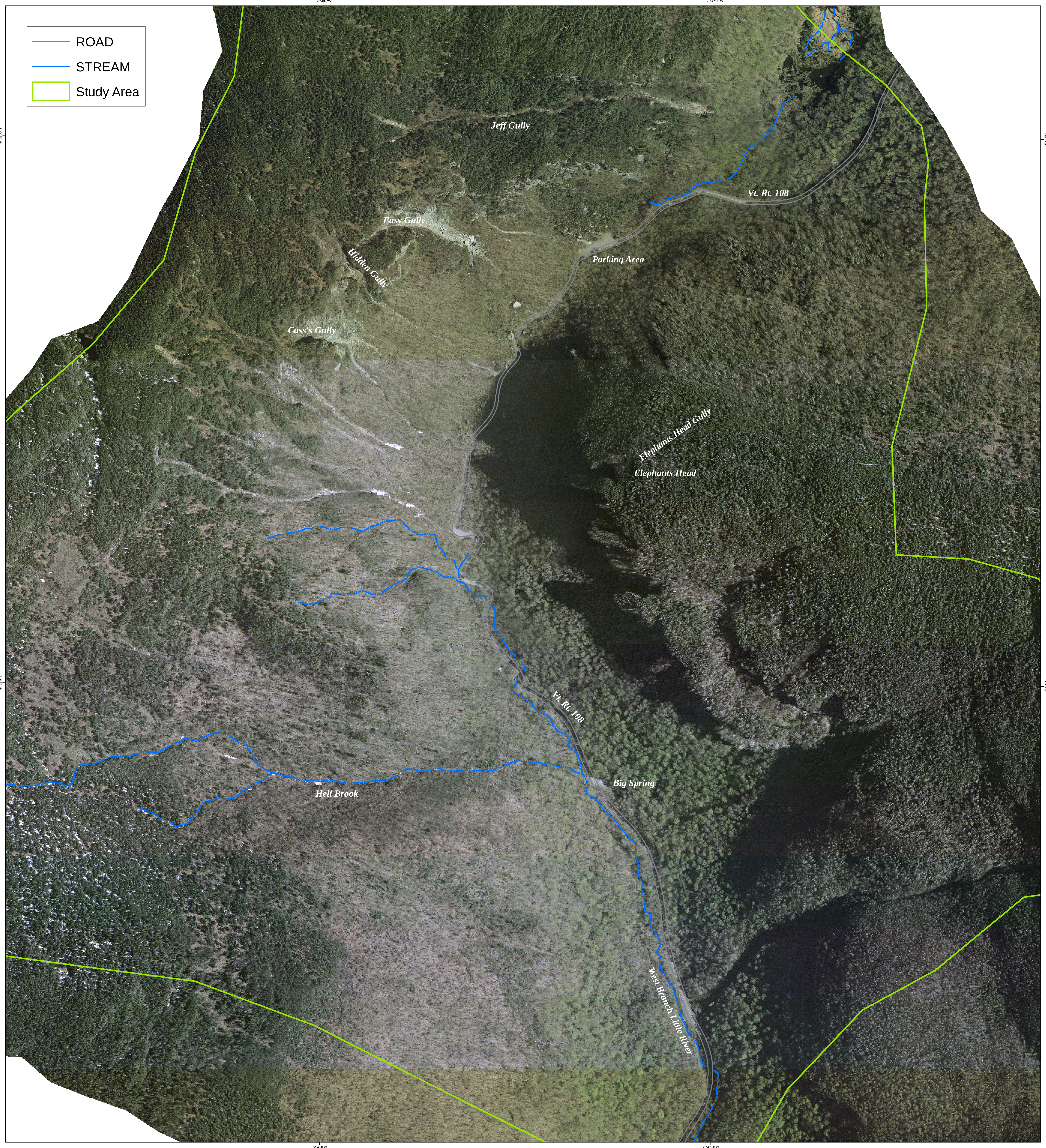
Topographic Map of Smugglers Notch Cambridge, Vermont

George Springston

3



Location Map



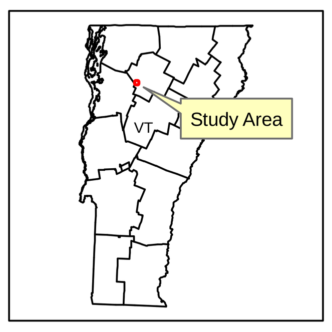
Scale 1:2,500

0 500 1,000 1,500 Feet

0 100 200 300 400 500 Meters

Orthophoto base produced by James W. Sewall Co. from aerial photos taken in May, 2007. Map produced for Vermont Geological Survey by Norwich University Geology and Environmental Science Department. Cartography by George Springston, March 25, 2008.

3



Location Map

May, 2007 Orthophoto of Smugglers Notch
Cambridge, Vermont
George Springston